TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 395

PENETRATION AND DURATION OF FUEL SPRAYS FROM A PUMP INJECTION SYSTEM

By A. M. Rothrock and E. T. Marsh
Langley Memorial Aeronautical Laboratory

Washington
October, 1931

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Summary

High-speed motion pictures were taken of individual fuel sprays from a pump injection system. The changes in the spray-tip penetration with changes in the pump speed, injection-valve opening and closing pressures, discharge-orifice area, injection-tube length and diameter, and pump throttle setting were measured. The pump was used with and without a check valve. In addition, the effects of the variables on the time lag and duration of injection were determined with an oscilloscope. The results show that the penetration of the spray tip, the time lag of injection, and the duration of injection can be controlled by the dimensions of the injection tube, the area of the discharge orifice, and the injection-valve opening and closing pressures.

Introduction

To determine the suitability of a given type of injection system for high-speed compression-ignition engines, it is necessary to know the operating characteristics of the system. One of the most important characteristics to be investigated is the formation and the development of the fuel spray. During the last five years the National Advisory Committee for Aeronautics has published considerable information on the effects of the various factors which control the formation and the development of the fuel spray. Investigations have been conducted with a mechanically operated injection valve and with automatic injection valves. In these investigations it was necessary to operate the injection system from a constant source of pressure because the purpose of the tests was to investigate the effects of such variables as the injection pressure, the spray-chamber density, and the discharge orifice design.

With pump injection systems, however, the injection pressure varies with pump speed and in some cases with the fuel quantity delivered. Tests already conducted (reference 1) have shown that the injection pressures affect the penetration of the fuel spray during the first few thousandths of a second. As this is the time available for injection in a high-speed compression-ignition engine, it is important to know how the pressure variations in a pump injection system will affect the fuel-spray penetration and dispersion. It is also advantageous to know the effects of such variables as the injection-tube length, the injection-tube diameter, the discharge orifice diameter, and the injection-valve opening and closing pressures on the penetration and dispersion of the fuel spray.

This report presents the results obtained from an investigation made at the Langley Memorial Aeronautical Laboratory, Langley Field, Va., to determine the effect of pump speed, the dimensions of the injection tube, the pump throttle setting, the discharge orifice diameter and the adjustment of the injection valve on the start, duration, penetration, and dispersion of the fuel spray. As far as was practicable the test conditions were the same as those used by Rothrock in his investigation of the hydraulics of fuel-pump injection systems. (See reference 2.) The injection valve and the fuel pump were the same as those described in reference 2. The pump was tested with and without a check valve.

Apparatus and Methods

A diagrammatic arrangement of the apparatus used in this investigation is shown in Figure 1. This apparatus is a modification of the N.A.C.A. spray photographic equipment (reference 3) used in taking high-speed motion pictures of a single spray discharge from a common-rail system. Two modifications have been made: a change from the common-rail system to the pump system of injection, and a change in the spray chamber so that continuous injections from a fuel pump into the compressed air would not fog the chamber and prevent photographs from being taken of a single spray.

In the modified spray chamber (fig. 3) a funnel was arranged in front of the nozzle to deflect the sprays into a reservoir. Releasing the funnel catch allowed the funnel to drop below the nozzle and permitted the spray to enter the spray chamber. With the proper timing the funnel uncovered the valve nozzle between pump discharges so that there was no interference between the spray and the funnel.

The pump tested was a six-cylinder commercial fuel pump. A cross section through one of the cylinders of the pump (fig. 2) shows its construction. The outlets from five of the pump plungers were by-passed to the oil reservoir and the sixth was connected to the injection valve with a seamless steel tube having an outside diameter approximately twice the inside diameter.

The injection pump was rotated by a variable-speed electric motor and was connected to the camshaft through a jaw clutch. The camshaft remained stationary until engaged by this clutch. It then made one revolution with the pump shaft. During this revolution of the camshaft, the funnel catch was released; the rotary switch completed the electric circuit between the condensers and the spark gap. The rotary switch and the pump were timed with the serrated coupling so that the spray was synchronized with the discharges of the condensers. The injection-valve closing pressure instead of opening pressure was measured because of the greater accuracy of this measurement. (See reference 2.) The injection-valve opening pressure was approximately 1.4 times the closing pressure.

The fuel oil used had a specific gravity of 0.85 and an absolute viscosity of 0.022 poise at 100° F.

Unless otherwise stated, all tests were made with a 0.020-inch diameter orifice and a 34-inch injection tube. The discharge orifice length-diameter ratio was 6:1 in all tests.

The procedure for taking a spray photograph was the same for all tests. The pump was brought up to the desired speed and the throttle opened for a few revolutions to expel all air from the injection line. Air was then blown through the spray chamber to clear the glass walls and to remove suspended oil particles. The air pressure, with the exception of one test, was raised to 200 pounds per square inch, a density of 1.1 pounds per cubic foot, which is equivalent to the density in the combustion chamber of an engine operating at a compression ratio of 14:1, and the funnel was raised and latched in position. When the desired film-drum speed was reached the pump throttle was again opened, and after several revolutions of the pump the clutch was engaged. A progressive series of photographs was thus recorded of the spray development. From these records the spray-tip penetration curves were obtained.

Stem-lift records of the injection-valve stem were also taken in a few cases to determine the movement of the valve stem under the pressure conditions in the injection valve. The method was the same as described in reference 2.

An oscilloscope (reference 4) was used to determine the start and duration of the spray when injected into the atmosphere. The curve of the pump cam and the point at which the pump by-pass port closed for the start of injection have been given in reference 2. This point, 132° of pump-cam travel, was used as a reference for plotting the oscilloscope data in pump degrees.

Test Results and Discussion

Spray-tip Penetration

The results of the tests are shown by graphs on which the penetration of the fuel spray-tip in the spray chamber is plotted against time. Tangents to these curves indicate the rate of penetration of the spray tip. A separate curve is plotted for each variable and the effect of the variable on spray-tip penetration is noted. Each curve is plotted from two or three tests under the same conditions. Additional checks were made when large variations appeared. Zero time on the graphs refers to the start of the spray from the orifice.

Effect of pump speed.- In reference 2 it was shown that varying the pump speed added to the initial pressure, approximately the valve-closing pressure, in the injection tube instantaneous values of pressure proportional to the velocity of the pump plunger. As the initial pressure was increased the ratio of the pressures created by the motion of the pump plunger to the total pressure at any instant decreased. It has also been shown in references 1 and 5 that both the maximum injection pressures and the injection-valve opening pressure affect the spray-tip velocity. However, as the rate-of-pressure rise, after the injection valve opens, decreases or as the ratio of the maximum pressure to the injection-valve opening pressure decreases it can be expected that the effect of the injection-valve opening pressure on the spray-tip penetration will increase and the effect of the maximum pressure will decrease. We can therefore expect that, in general, as the injection-valve opening pressure is increased the effect of pump speed on spray-tip penetration will decrease.

In reference 2 it has also been shown that as the pump speed is decreased a speed is reached below which the pressure waves originating at the fuel pump are not sufficient to hold the injection-valve stem from the seat. This value of speed depends on the injection-pump plunger diameter, the pump-cam contour, the injection-tube diameter, the initial pressure in the injection tube, the injection-valve opening and closing pressures, and the pressure into which the discharge takes place. It is, within practical limits, independent of the injection-tube length. For speeds below this value the injection-valve stem will tend to oscillate, thereby opening and closing the injection valve. The phenomenon is sometimes accompanied by a chattering of the injection-valve stem against its seat during the injection period. When this phenomenon occurs the fuel discharge instead of consisting of a single spray will consist of two or more individual sprays following each other, generally in quick succession. Under certain circumstances the stem may not lift sufficiently to expose a flow area greater than the discharge orifice area. In this case the stem and seat together act as a variable-area orifice. Owing ~~Due~~ to restriction to flow the spray will not have the penetrating ability possible were the stem fully lifted.

The effect of pump speed on the spray-tip penetration at an injection-valve closing pressure of 2,000 pounds per square inch is shown in Figure 4. In no case was there evidence of primary sprays before the main spray at pump speeds above 760 r.p.m. The variation in maximum pressures and in the rate-of-pressure rise was sufficient to cause the spray-tip penetration to increase with pump speed.

Figure 5 shows the effect of low pump speeds on the spray-tip penetration at an injection-valve closing pressure of 2,500 pounds per square inch. The figure shows that at the two lower speeds primary sprays appeared before the main spray. These primary sprays were caused by the seating of the injection-valve stem after the initial opening. After the second lifting of the stem the pressure was sufficient to keep the injection-valve stem off its seat. If the main sprays at the two lower speeds are compared with those at the higher speeds (fig. 5-B) it is seen that the penetration of the main spray is not appreciably affected by the pump speed. It may be concluded that in this case the injection-valve closing pressure was sufficiently high so that the effect of the rate-of-pressure rise and maximum pressures had no appreciable effect on the spray-tip penetration of the main sprays.

At low pump speeds and with an injection-valve closing pressure of 500 pounds per square inch, the rate-of-pressure rise and the maximum pressures materially influenced the penetration (fig. 6). At the two lower speeds primary sprays occurred.

Figure 7 shows a spray photograph and stem-lift record taken at a pump speed of 190 r.p.m. with atmospheric pressure in the spray chamber. The small lines at the top of the stem-lift record were caused by a spark gap placed in series with the main gap for taking the photographs. Consequently, each line corresponds to a spray photograph. Because the stem record extended for more than a single revolution of the film drum the spray photographs and the stem record are not synchronized. The injection-valve stem oscillated, thus opening and closing the injection valve and causing a series of sprays. The bouncing of the stem was eliminated when the chamber pressure was increased to 200 pounds per square inch, because of the additional force on the stem. However, when the pump speed was decreased to 108 r.p.m. (fig. 8) the bouncing of the stem during the whole injection period again occurred though the chamber pressure was 200 pounds per square inch. Comparison of Figures 7 and 8 shows that in the former the stem lift and consequently the pressures were higher than in the latter.

<u>Effect of injection-valve closing pressure</u>.- Figure 9 shows the effect of the injection-valve closing pressure on the penetration of the tip of the main spray for a pump speed of 470 r.p.m. The records showed that there

were primary sprays with injection-valve closing pressures of 1,500 pounds per square inch or greater. The figure shows that the penetration of the main spray increases as the injection-valve closing pressure was increased until a value of 1,500 pounds per square inch is reached. For this pressure the spray-tip penetration decreased. As the injection-valve closing pressure was further increased the penetration again increased. The decrease in the penetration at the injection-valve closing pressure of 1,500 pounds per square inch was probably caused by the injection-valve stem throttling the flow of fuel past the valve seat. Above this injection-valve closing pressure, although throttling still occurred as has been shown in reference 2, the pressure at the start of injection was sufficient to give the spray the increased penetration.

The penetration of both the primary and main sprays for the injection-valve closing pressures of 1,500 and 2,000 pounds per square inch is shown in Figure 10. It is seen that the primary spray as well as the main spray penetrated at a faster rate as the injection-valve closing pressure was increased.

Figure 11 shows the effect of the injection-valve closing pressure on the spray-tip penetration for a pump speed of 760 r.p.m. No primary sprays were observed at this speed. However, as was the case with 470 r.p.m., a minimum penetration occurred at a particular injection-valve closing pressure, 2,000 pounds per square inch.

At low injection-valve closing pressures and a pump speed of 760 r.p.m., it was shown in reference 2 that the pressure-wave phenomenon caused secondary discharge after cut-off occurred at the fuel pump. Secondary discharges did not occur with the higher injection-valve closing pressures. The photographs showed these secondary discharges with the low valve closing pressures, but because of the fogging of the chamber the photographs were not clear enough to reproduce on a half-tone print.

Effect of injection-tube diameter.- As shown in reference 2, it is advisable to use an injection-tube diameter equal to or slightly greater than the critical tube diameter so that the flow through the injection tube will be laminar with a resultant small pressure loss caused by friction. Figure 12-A shows that the penetration at a pump speed of 760 r.p.m. was nearly the same for all injection-tube diameters even when diameters considerably less than the critical diameter (0.098 in.) were employed. For the conditions shown in Figure 12-A it may be concluded that the injection-valve opening and closing pressure controlled the spray-tip penetration.

For the pump speed of 470 r.p.m. (fig. 12-B) the smaller tube gave the lower spray-tip penetration. As the test conditions caused primary starts at the beginning of the spray (fig. 10) the drop in rate of penetration was probably due to their formation.

To illustrate the influence of these primary sprays in this instance, a comparison of Figure 10 with Figure 12-B shows that the primary spray penetration for the 0.076-inch tube falls below the curve for the primaries of the 0.041- and 0.059-inch diameter tubes, indicating lower penetration for the 0.076-inch tube. However, the main spray for the 0.076-inch tube shows greater penetration. The spray photographs for the 0.041- and 0.059-inch diameter tubes show primaries but the main sprays are not clear enough to be measured directly. Measurement of the clearest main spray (0.059-inch tube) shows the main spray penetration to be the same as that for the 0.076-inch tube.

The increase in penetration for the 0.125-inch tube (470 r.p.m.) is due to laminar flow which exists in the tube. As shown in reference 2, turbulent flow in a tube results in friction and pressure losses which give a low initial stem lift and a slow rise in pressure at the injection valve. Both conditions aid the formation of primary sprays. With laminar flow these conditions are lacking and a faster rate-of-pressure rise results which increases the penetration.

<u>Effect of injection-tube length</u>.- Figure 13 shows the effect of the injection-tube length on the spray-tip penetration. The results show that there was little variation in the spray-tip penetration for tube lengths between 34 and 70 inches. Because of the limitations of the apparatus it was not possible to test injection-tube lengths of less than 34 inches. However, it was shown in reference 2 that the instantaneous pressures showed little variation with injection-tube lengths of from 4 to 34 inches. Consequently it may be assumed that the injection-tube length does not have an appreciable effect on the penetration of the fuel spray.

Effect of pump-throttle setting.- Increase in the pump-throttle setting (fig. 14) gave decreased penetration. The injection periods for low throttle settings were short but the spray reached the maximum penetration that could be measured before cut-off occurred. The effect of the initial pressure rise with early cut-off should have a determining effect on the action of the spray. From stem-lift records (reference 2, fig. 17) the pressure rise as the valve stem is first lifting is more rapid at the lower throttle setting. The higher initial velocity of the spray gives, therefore, an increased rate of penetration for the lower throttle settings.

Effect of check valve in pump.- With no check valve in the pump there was a slight increase in the rate of penetration over that obtained by using a check valve, as is shown by Figure 15. The results without the check valve were erratic. In reference 2, Figure 19, the stem-lift curve obtained without a check valve in the pump shows a faster rate of stem lift than with a check valve, indicating a greater pressure rise and greater initial spray-tip velocity than that obtained with a check valve in the pump, but the injection period was materially decreased. However, later results have shown that removing the check valve also decreases the total fuel quantity discharged.

With no check valve between the pump and the injection tube, the tube often became air-locked causing a pulsating flow in the injection tube, but no injection. The air lock was probably caused by air leakage from the spray chamber past the injection valve seat. This air lock persisted even after the injection-valve closing pressure had been raised to 4,500 pounds per square inch. The other five plungers would discharge regularly into the oil reservoir. With the check valve in the pump, any air in the line was forced out during the first few revolutions.

Effect of open nozzle.- The open nozzle used in these tests was fitted with a ball-check valve close to the nozzle to prevent leakage of air into the injection line, as recommended in reference 7. With the check valve in the pump a marked increase in the rate of penetration was noted at 760 r.p.m. (fig. 16) over that obtained without the check valve. The increase at 470 r.p.m. was not so noticeable. The increase in rate of penetration was due to the fact that the closing of the check valve trapped an initial pressure in the injection line equal to the spray-chamber pressure. This initial pressure aided in building up higher pressures in the injection tube. Furthermore, the check valve lessened the probability of the formation of an air pocket in the injection line.

The penetration obtained with the open nozzle with and without the check valve at the pump was less than that obtained with the closed nozzle under the same conditions.

Effect of orifice diameter.- Figure 17 shows the results obtained with a 0.030-inch diameter orifice at pump speeds of 470 and 760 r.p.m. These curves show a lower rate of penetration than the corresponding series for the 0.020-inch orifice (fig. 15-B) and the photographic record shows a decreased injection period.

Values for the instantaneous pressures (fig. 18) at the orifice, computed by the method presented in reference 2, show that with the 0.020-inch orifice the instantaneous pressures were much higher than with the 0.030-inch orifice. These higher pressures resulted in a higher rate of penetration for the smaller orifice.

Time-Lag and Duration of Injection

Curves were plotted from the oscilloscope data to show the following: the start of injection, i.e., the appearance of the first faint spray; the beginning of the main spray; the stop of the main spray; and the stop of injection.

The point at which the pump inlet port closed is indicated on all the graphs at 132° of pump travel. The main spray in no case started below this position. When injection started below this position it was caused by the fact that the wave originating at the pump plunger was not entirely dissipated through the by-pass valve. This phenomenon of injection starting before the by-pass valve closes has also been observed in the N.A.C.A. single-cylinder pumps. It can be eliminated by enlarging the by-pass area.

In the figures the solid curves represent the start and stop of injection and the broken curves represent the start and stop of the main spray. In some cases where the start of the main spray was irregular the points are shown on the figure but a curve has not been drawn through them.

Effect of pump speed.- Injection lag in pump degrees decreased with increase in pump speed (fig. 19) and with decrease in the injection-valve closing pressure. (See figs. 19 and 21.) The injection period in degrees increased for increase in pump speed and for decreased valve closing pressure.

The injection lag in seconds decreased with increased pump speed and with decreased valve closing pressure. (See fig. 20.) The lag increased very rapidly as the pump speed was dropped below 400 r.p.m. for both high and low valve closing pressures because of the low intensity of the initial pressure waves originating at the pump. Above 400 r.p.m. the injection lag tended to become independent of the pump speed.

The duration of the injection after the by-pass valve opened increased for decreased valve opening pressure. Figure 20 shows that duration of injection after the by-pass valve opened remained at approximately 0.003 second for the high valve closing pressure and for pump speeds above 250 r.p.m. For the low valve closing pressure the duration of injection after cut-off increased with increased speed from 0.003 second at 250 r.p.m. to 0.0056 second at 750 r.p.m. The increased intensity of the pressure waves of the higher pump speeds had more effect on the duration of injection at the lower valve opening pressures.

The injection period in seconds decreased very slowly with increased speed above 400 r.p.m. Below 400 r.p.m. the injection period increased rapidly with decreased speed, the injection period at 250 r.p.m. and 150 r.p.m. being two and three times, respectively, the injection period at 750 r.p.m. The total injection period was shorter for the higher valve closing pressure. This result is in accord with the results presented in reference 2.

Effect of injection-valve closing pressure.- The valve closing pressure (fig. 21) shows a constant initial injection start up to a valve closing pressure of 1,200 pounds per square inch. An increase in the valve closing pressure above this value gave a 5° later injection start which remained constant for the valve closing pressures between 1,600 and 2,700 pounds per square inch. This increase in the lag of 5° is equivalent to 0.00011 second or the time required by a pressure wave to twice traverse the injection tube. (See reference 2.) It may be concluded that the initial wave was sufficient to open the injection valve with injection-valve closing pressures up to 1,200 pounds per square inch but that for pressures above 1,600 pounds per square inch it was necessary for the initial wave to be reenforced by a reflected wave. The irregularities in the start of the main spray were accompanied by irregularities in the cut-off and the disappearance of the spray.

<u>Effect of injection-tube diameter</u>.- The injection lag decreased as the injection-tube diameter was increased up to 0.080 inch. (See fig. 22.) Further increase in the tube diameter caused the lag to increase. Reference 2, Figure 29, shows that the critical tube diameter for both 450 and 750 r.p.m. is approximately 0.098 inch. Below this value the increase in injection lag is caused by the increased resistance to flow. Above the critical value, increase in injection lag is caused by the decrease in the intensity of the initial pressure wave. For a different speed from those tried, a minimum should be expected at a point corresponding to the critical tube diameter for that particular speed. It is particularly interesting to note that increasing the injection-tube diameter decreases the time lag of the cut-off of the fuel spray after cut-off at the pump.

<u>Effect of injection-tube length</u>.- The injection lag and injection period did not vary with the tube lengths of 34 and 74 inches. It is difficult to explain why the 74-inch tube did not show a greater lag than that observed with the 34-inch tube. The apparent discrepancy is undoubtedly caused by the size and shape of the by-pass passages in the pump.

<u>Effect of pump-throttle setting</u>.- Except at very low throttle settings there was no variation in injection lag with throttle setting. (See fig. 23.) The sharp increase in the injection lag between 1/2 and 1/4 throttle setting was caused by the variation in the size and shape of the pump plunger passage for the by-passed fuel.

<u>Effect of check valve in pumps</u>.- The effect of the check valve at the pump on injection lag and injection

period was quite noticeable. Table I shows that the injection lag increased on removal of the check valve. This was due to the fact that no initial pressure was trapped in the injection tube to aid in the building up of pressure as has been explained in reference 2.

The duration of injection after cut-off at the pump also decreased when the check valve was removed because at cut-off the pressure in the injection tube dropped very quickly to the pressure in the suction chamber. With no check valve the injection lag did not decrease with increased speed, although the injection period was longer with a higher speed.

Table I

Effect of check valve on duration of injection

Injection-tube length - 34 inches

Injection-tube inside diameter - 0.125 inch

Pump speed - 750 r.p.m.

	With check valve	Without check valve
Start of injection	130°	138°
Start of main spray	135°	147°
Stop of main spray	172°	173°
Stop of injection	179°	177°

<u>Effect of open nozzle</u>.- The injection lag for the open nozzle decreased with increased pump speed and the injection period increased. (See Table II.) As the injection-valve closing pressure of a closed nozzle is reduced the characteristics of the closed nozzle approach those of the open nozzle. Therefore the open nozzle data are comparable to those obtained with the closed nozzle with a valve closing pressure of 500 pounds per square inch. The open nozzle shows a much longer injection period than the closed nozzle at a valve closing pressure of 500

pounds per square inch. The shorter injection period of the closed nozzle is due to the earlier seating of the valve stem after cut-off.

Table II

Comparison of duration of injection with open and with closed nozzle

Injection-tube length - 34 inches

Injection-tube inside diameter - 0.125 inch

	Open nozzle		Closed nozzle V.C.P. - 500 lb./sq.in.
	470 r.p.m.	750 r.p.m.	750 r.p.m.
Start of injection	127°	126°	125°
Start of main spray	134°	132°	132°
Stop of main spray	176°	184°	177°
Stop of injection	190°	217°	189°

Conclusions

The test results presented show that fuel-injection pumps designed for high-speed compression-ignition engines have satisfactory operating characteristics over the speed range which is encountered under load in ordinary practice. At low speeds, such as are used for starting and idling, the fuel injection takes place as a series of sprays, because the fuel pressures originating at the pump are not sufficient to maintain high injection pressures at the discharge orifice of the injection valve. The results also show that the fuel-spray characteristics and the duration and start of injection are affected by the injection-tube diameter, the injection-valve opening and closing pressures, the dischrage-orifice area, the pump throttle setting, and check valves placed in the system.

The particular conclusions are:

1. Increasing the injection-valve opening and closing pressure increases the spray-tip penetration, decreases the duration of the injection, and increases the tendency for primary sprays to appear before the start of injection.

2. Increasing the pump speed increases the spray-tip penetration with low injection-valve opening and closing pressures, but has little effect on the penetration for high injection-valve opening and closing pressures; decreases the injection lag; increases the duration of the injection in pump degrees; and decreases the tendency for primary discharge to occur.

3. Increasing the injection-tube diameter from a value below the critical diameter to a value equal to the critical diameter decreases the time lag of injection and the duration of injection. Increasing the injection-tube diameter from a value equal to the critical diameter to a value greater than the critical tube diameter increases the time lag of injection and decreases the duration of injection.

4. Increasing the injection-tube diameter decreases the time lag between cut-off at the fuel pump and cut-off of the fuel spray.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 24, 1931.

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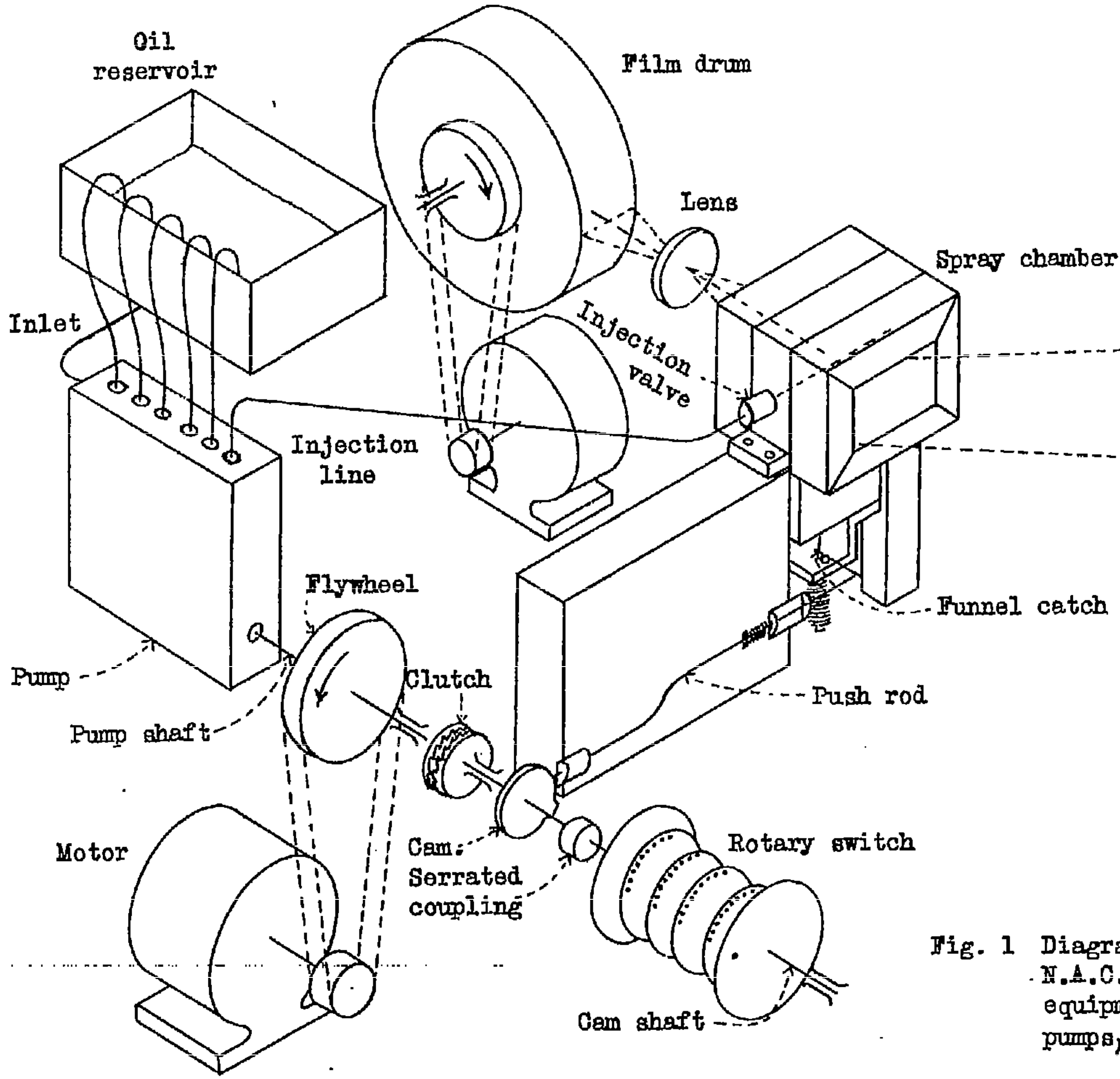

Fig. 1 Diagrammatic arrangement of N.A.C.A. spray photographic equipment for use with fuel pumps.

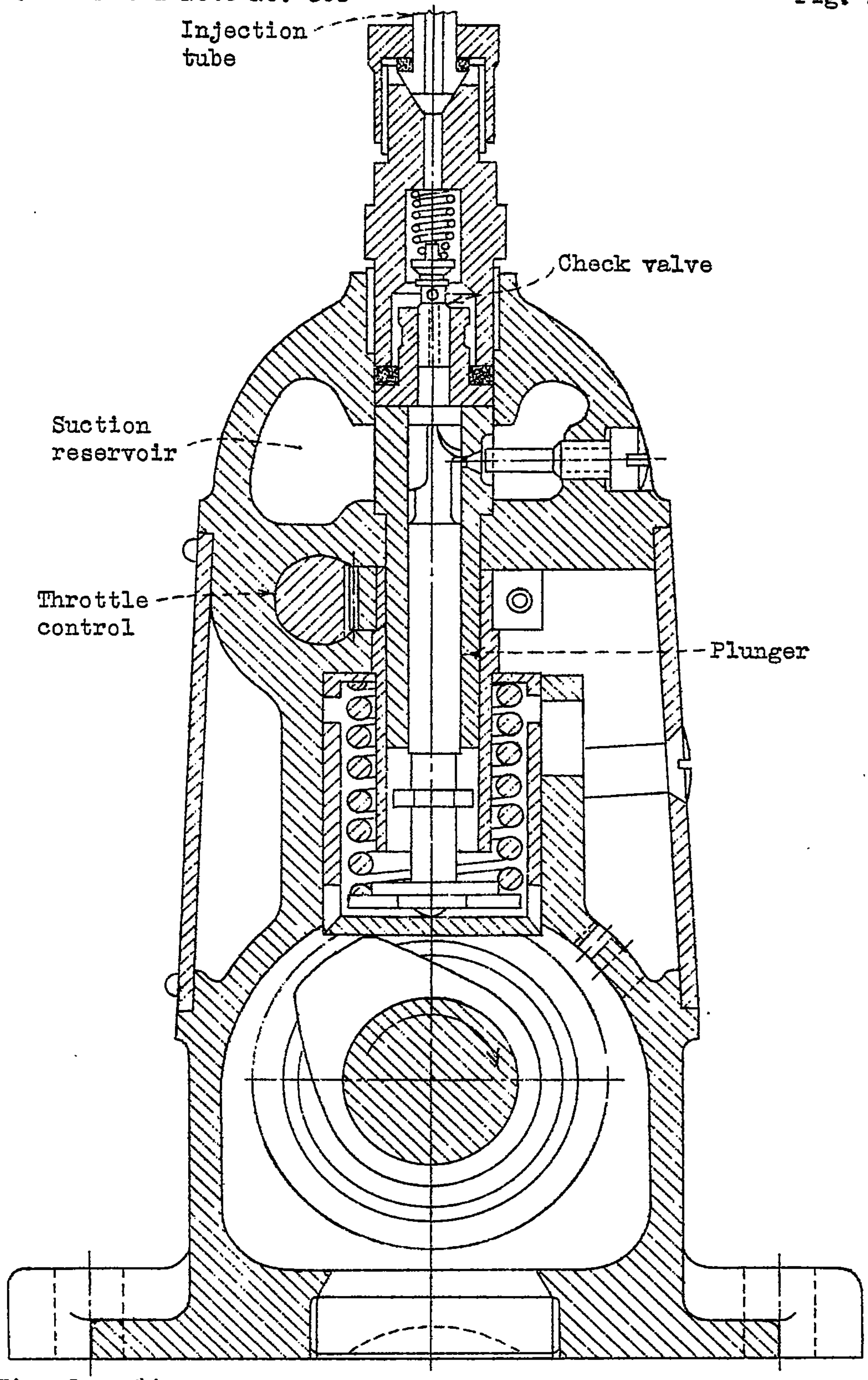

Fig. 2 Diagrammatic sketch of fuel pump used in tests.

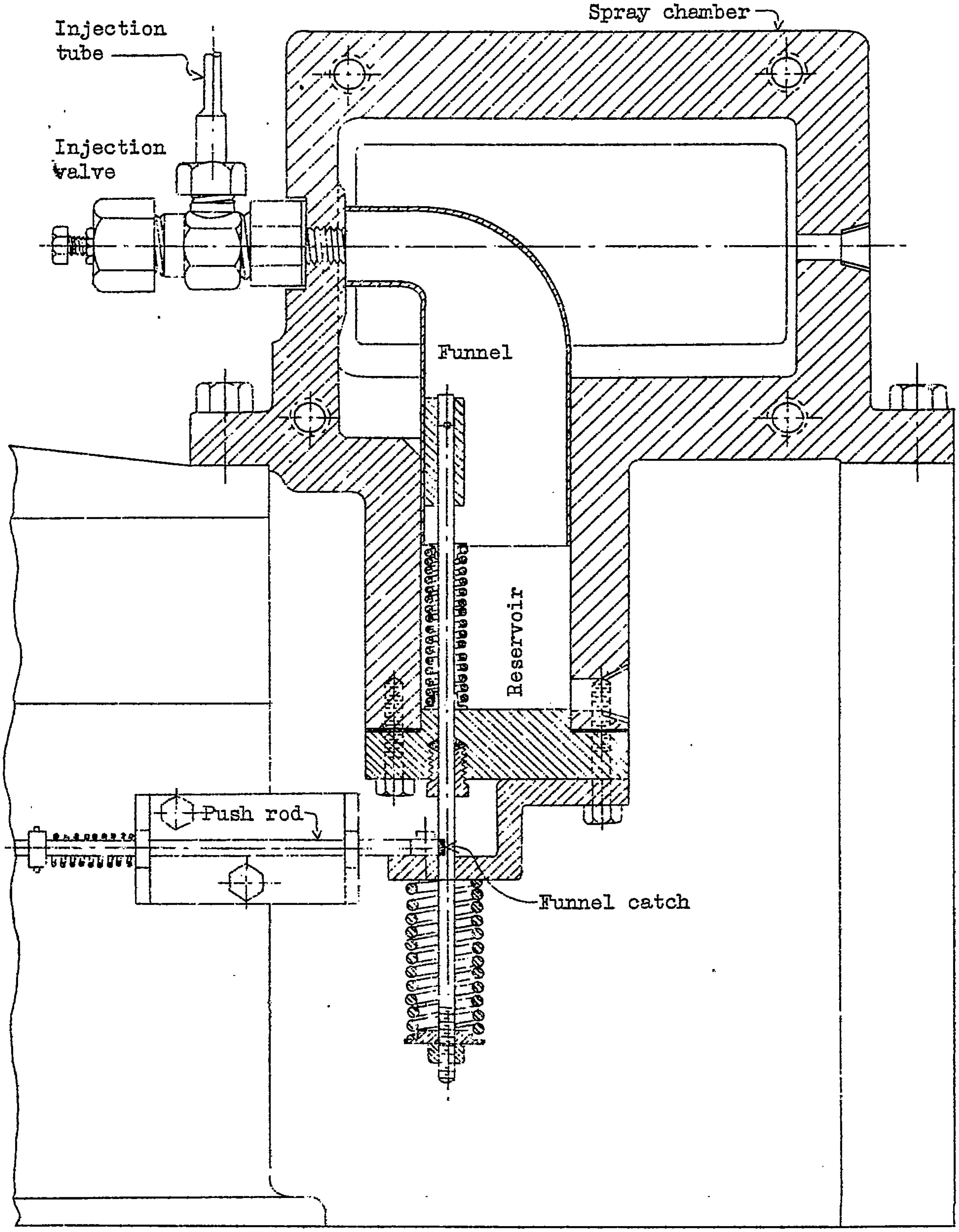

Fig.3 Spray chamber for use with fuel pumps

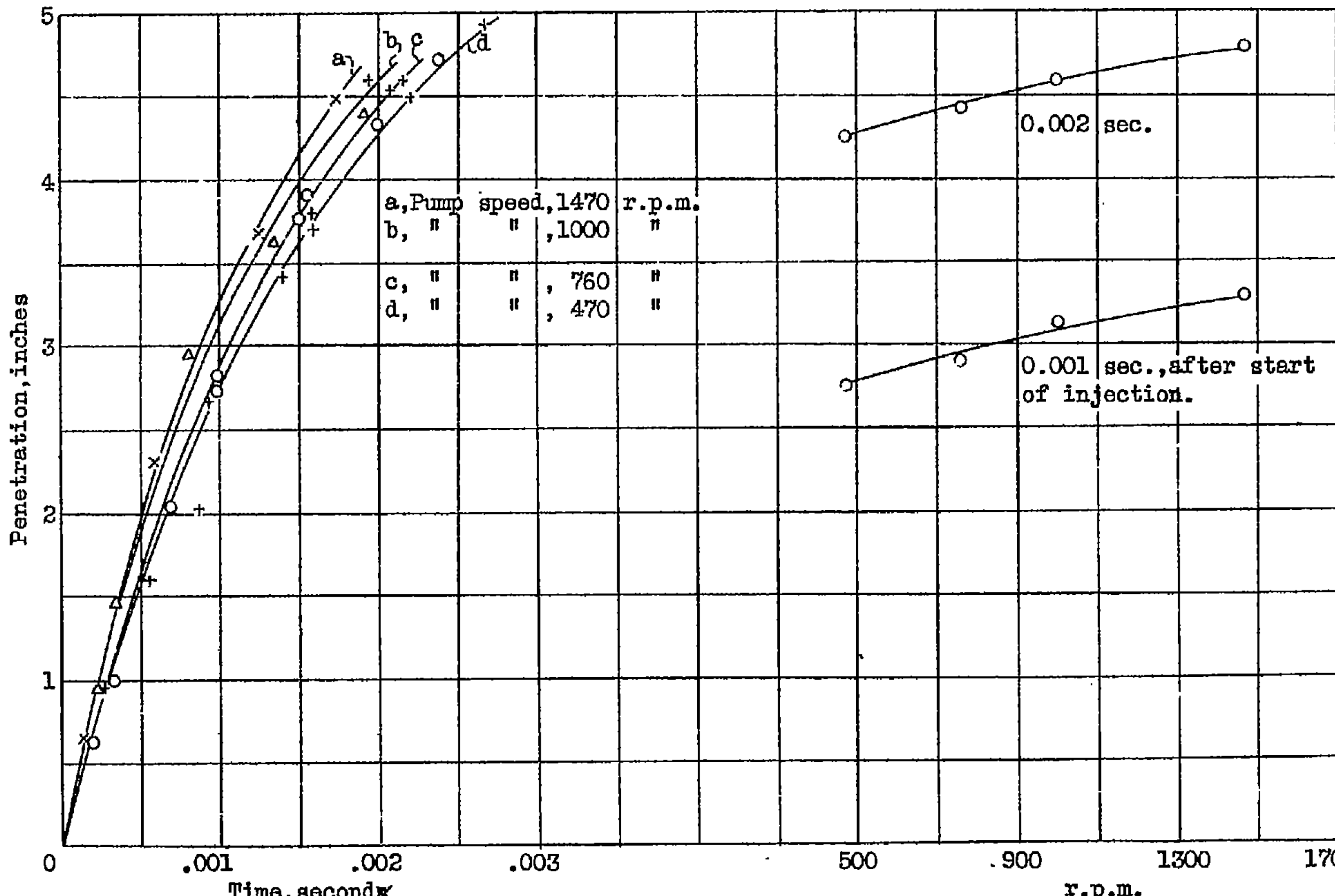

Fig.4 Effect of pump speed on penetration. Valve closing pressure,2000 lb./sq. in. Tube length,34 in. Injection tube inside diameter,0.125 in. Orifice diameter,0.020 in.

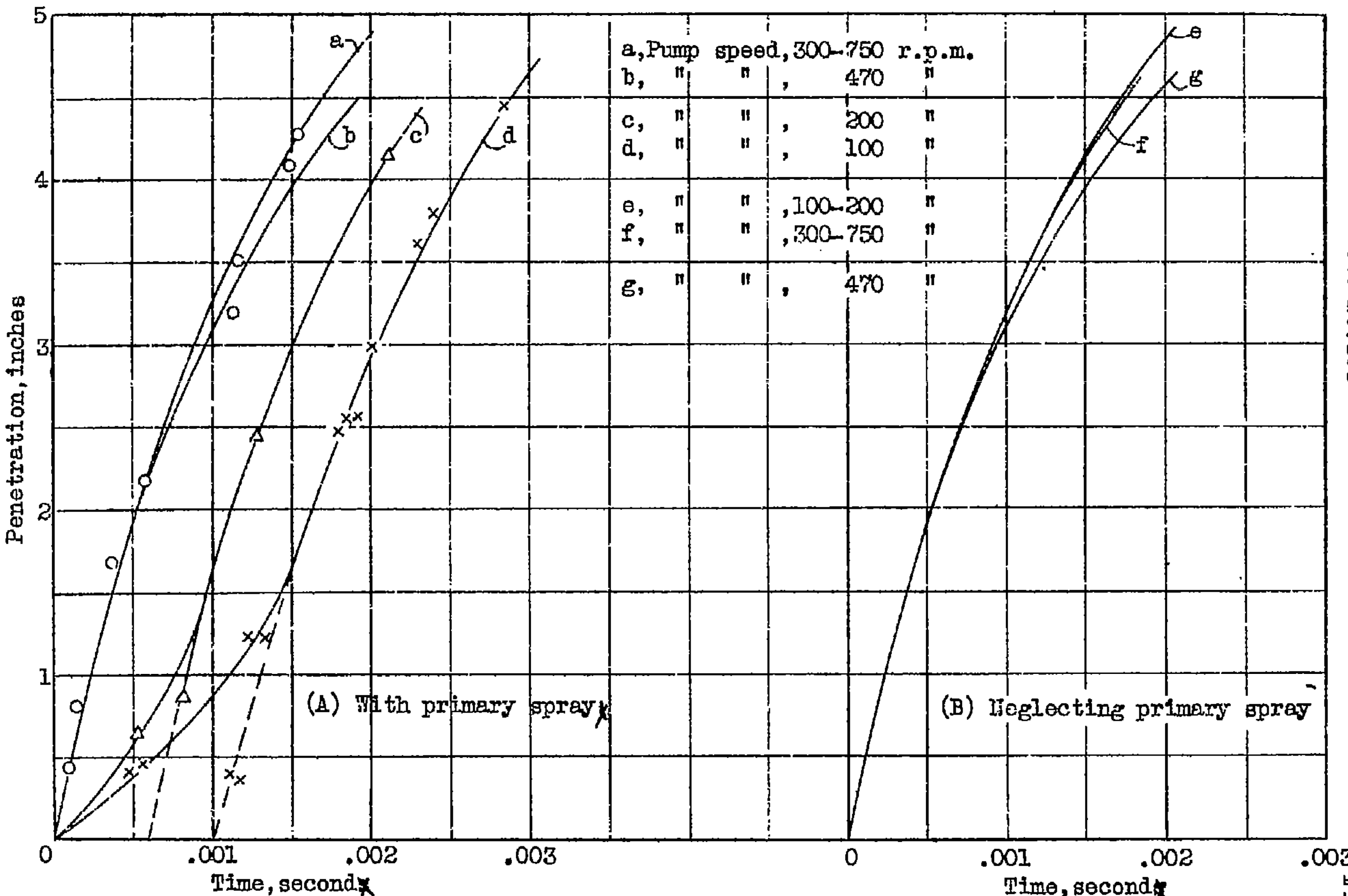

Fig.5 Effect of pump speed on spray-tip penetration at high injection-valve closing pressure.
Injection-valve closing pressure,2500 lb./sq. in. Tube length,34 in. Injection tube inside diameter,0.125 in. Orifice diameter,0.020 in.

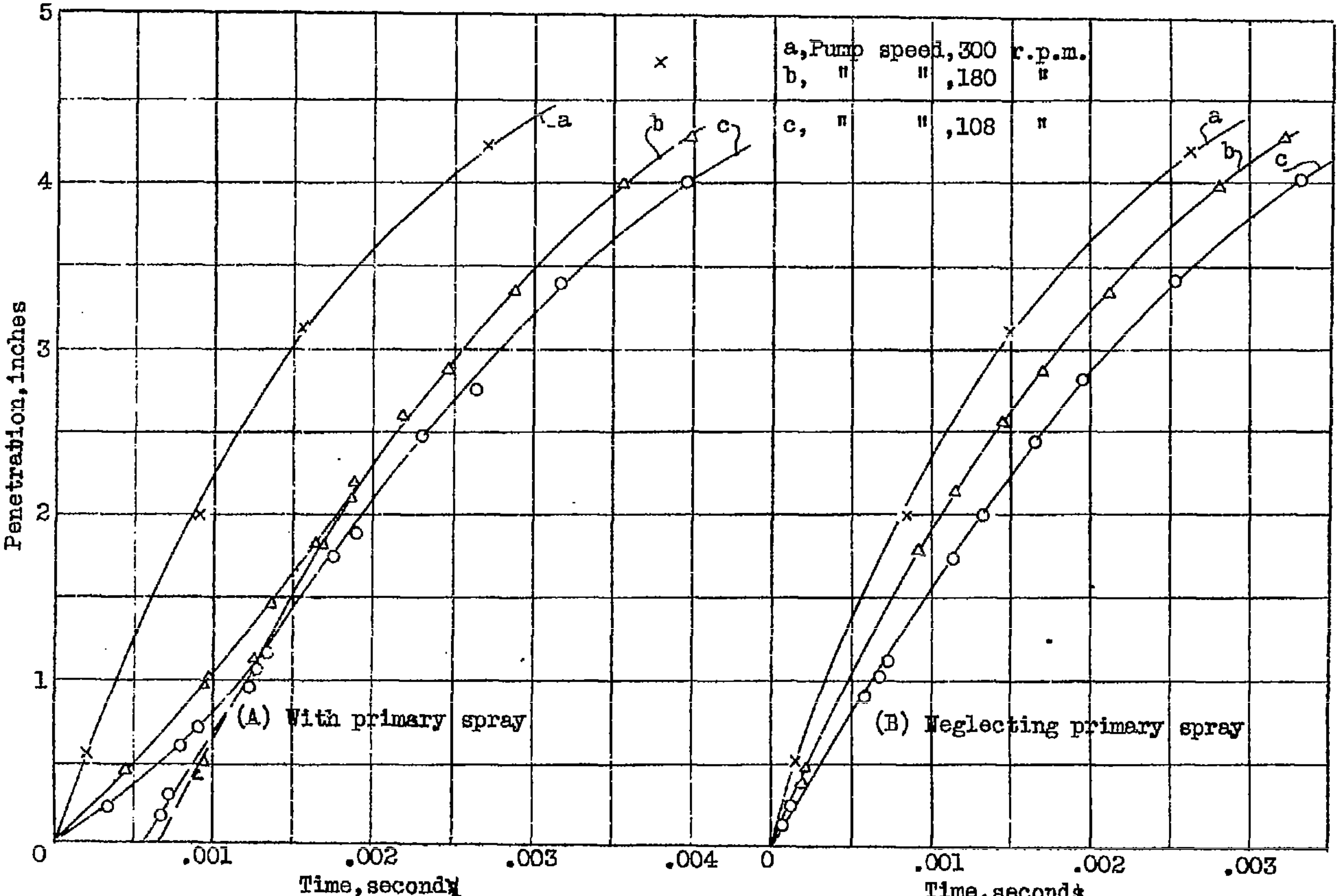

Fig.6 Effect of pump speed on spray-tip penetration at low injection-valve closing pressure. Injection-valve closing pressure, 500 lb./sq. in. Injection-tube inside diameter, 0.125 in. Tube length, 34 in. Orifice diameter, 0.020 in.

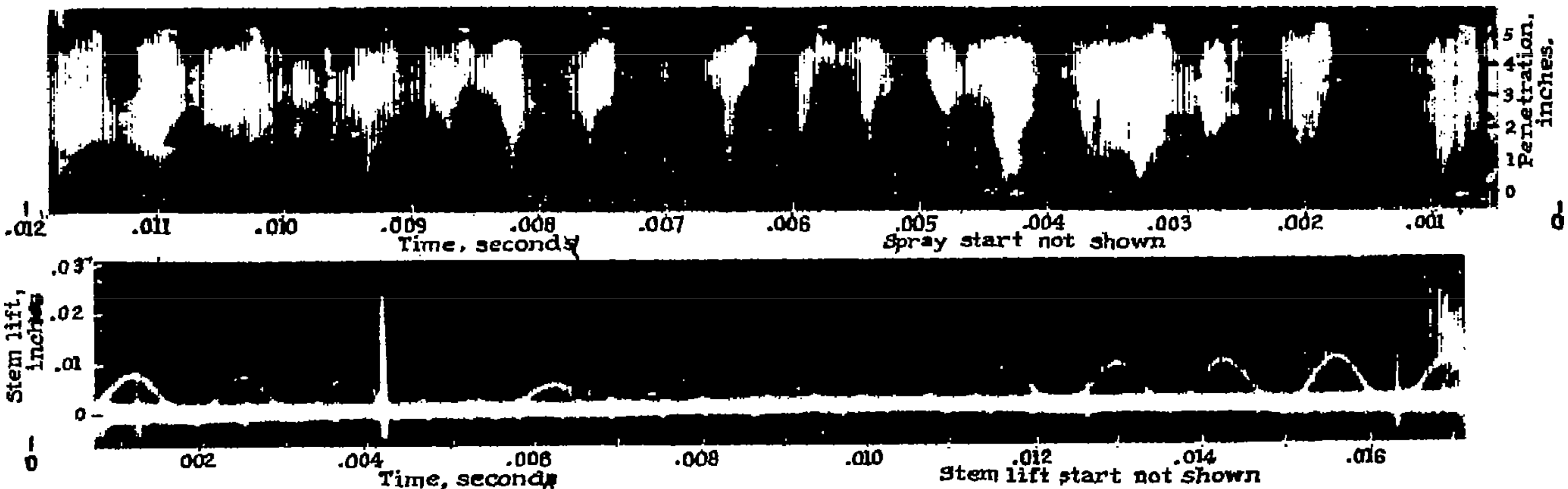

Fig.7 Spray photograph and stem-lift record at low pump speed.
Pump speed,190 r.p.m. Injection-valve closing pressure,500 lb. per sq. in.
Injection-tube inside diameter,0.125 in. Tube length,34 in. Spray chamber density,0.0765 lb. per cu. ft.

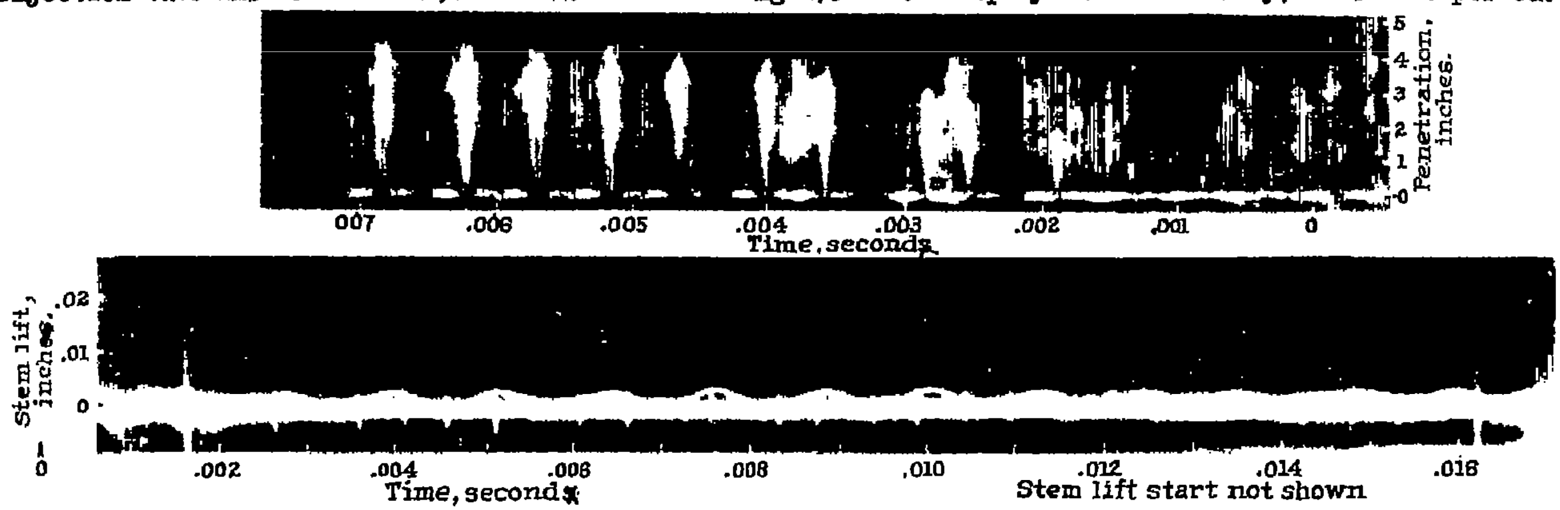

Fig.8 Spray photograph and stem-lift record at low pump speed.
Pump speed,108 r.p.m. Injection-valve closing pressure,500 lb. per sq. in.
Injection-tube inside diameter,0.125 in. Tube length,34 in. Spray chamber density,1.11 lb. per cu. ft.

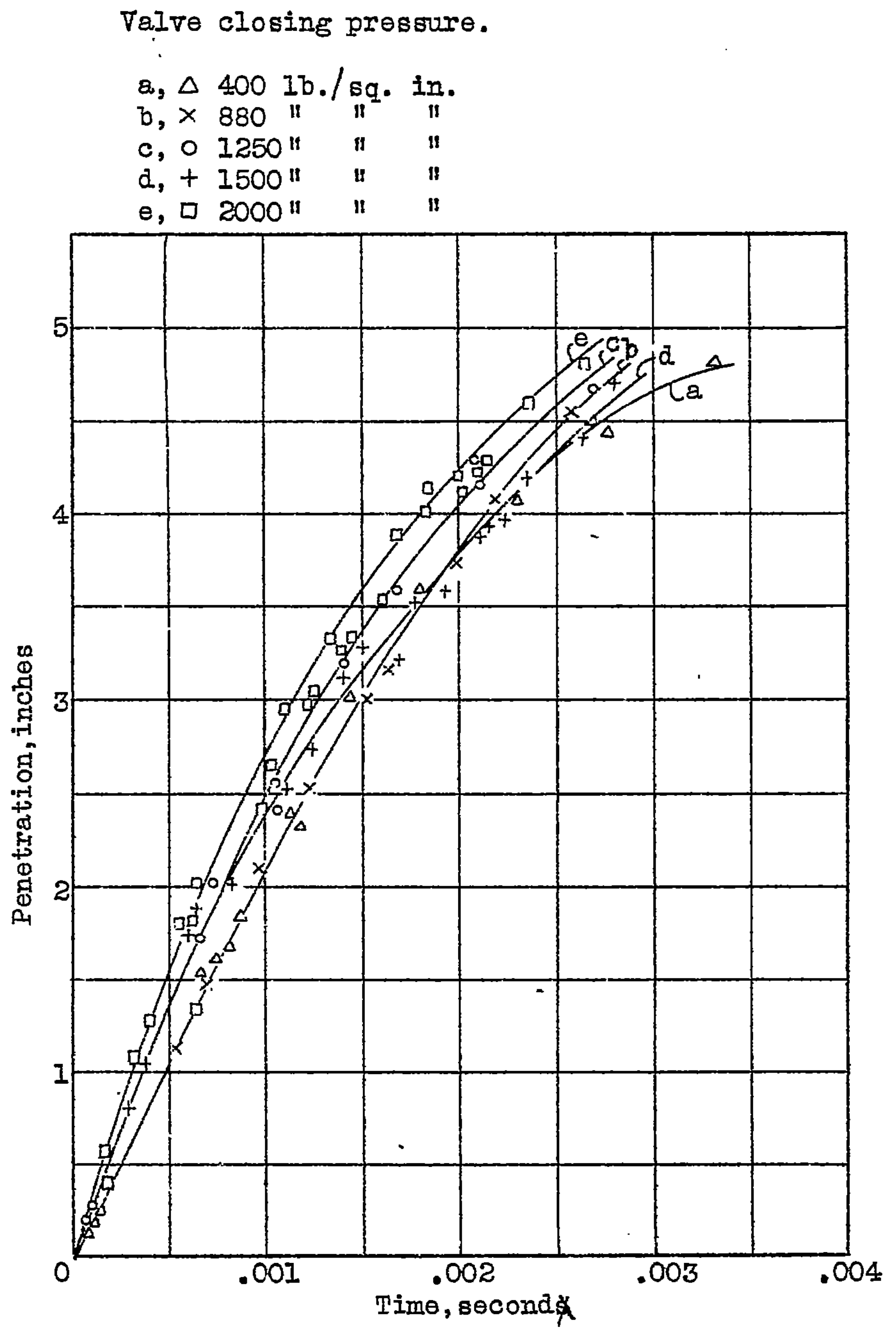

Fig.9 Effect of injection-valve closing pressure on spray-tip penetration. Pump speed, 470 r.p.m. Injection-tube inside diameter, 0.076 in. Tube length, 34 in. Orifice diameter, 0.020 in.

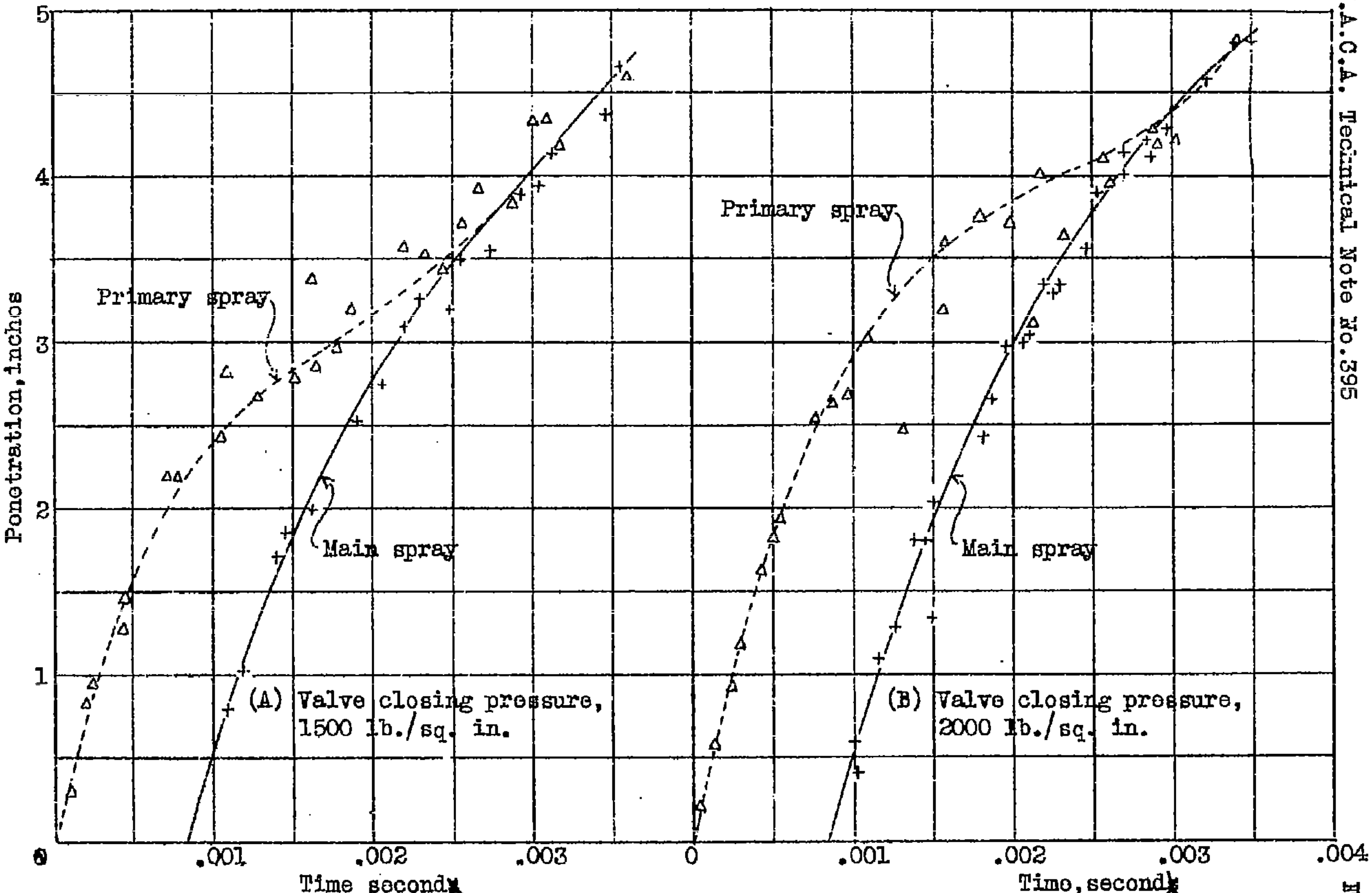

Fig.10 Effect of injection-valve closing pressure on spray-tip penetration of primary and main sprays. Pump speed, 470 r.p.m. Injection-tube inside diameter, 0.076 in. Tube length, 34 in. Orifice diameter, 0.020 in.

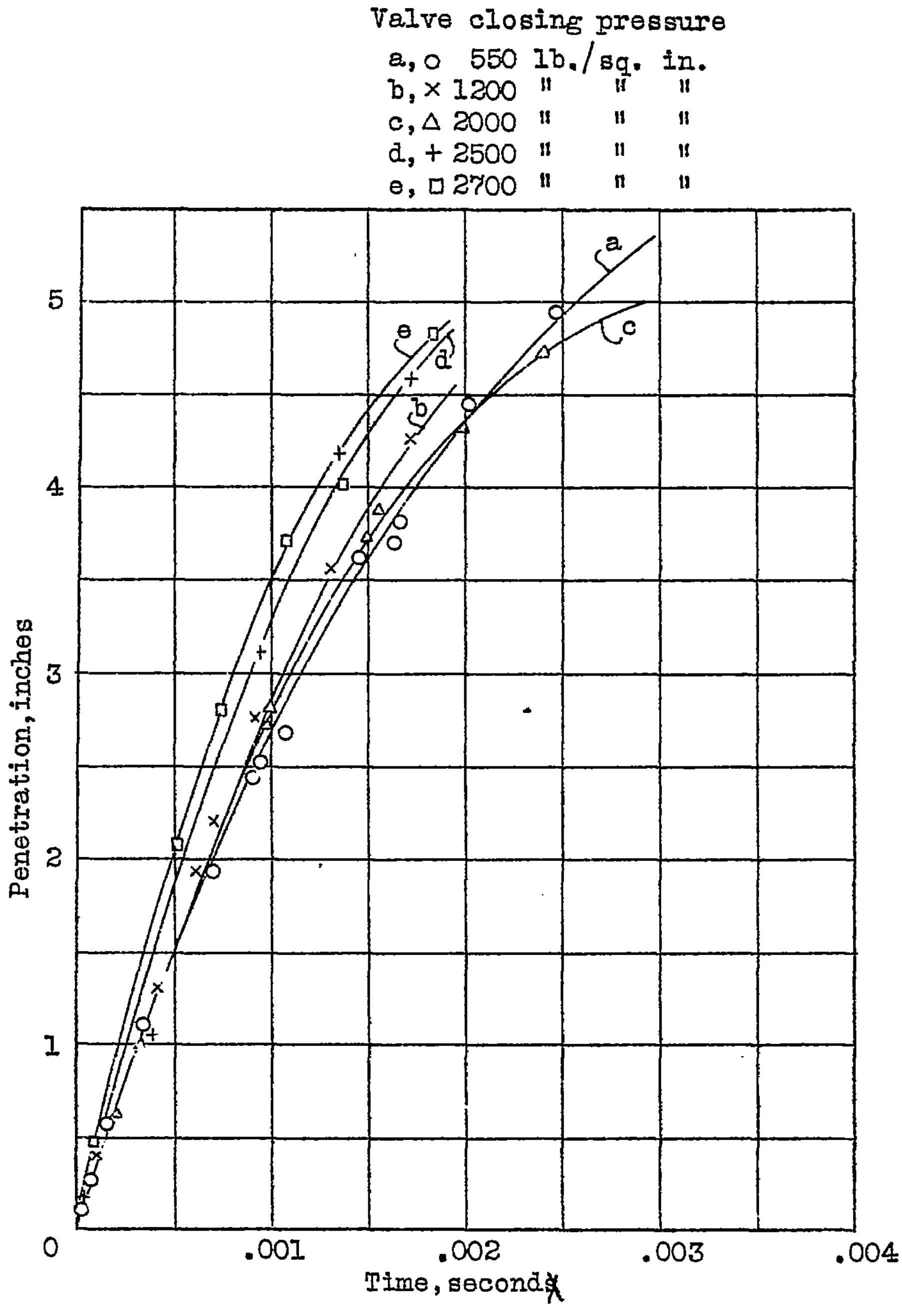

Fig.11 Effect of injection-valve closing pressure on spray-tip penetration. Pump speed, 760 r.p.m. Injection-tube inside diameter, 0.125 in. Tube length, 34 in. Orifice diameter, 0.020 in.

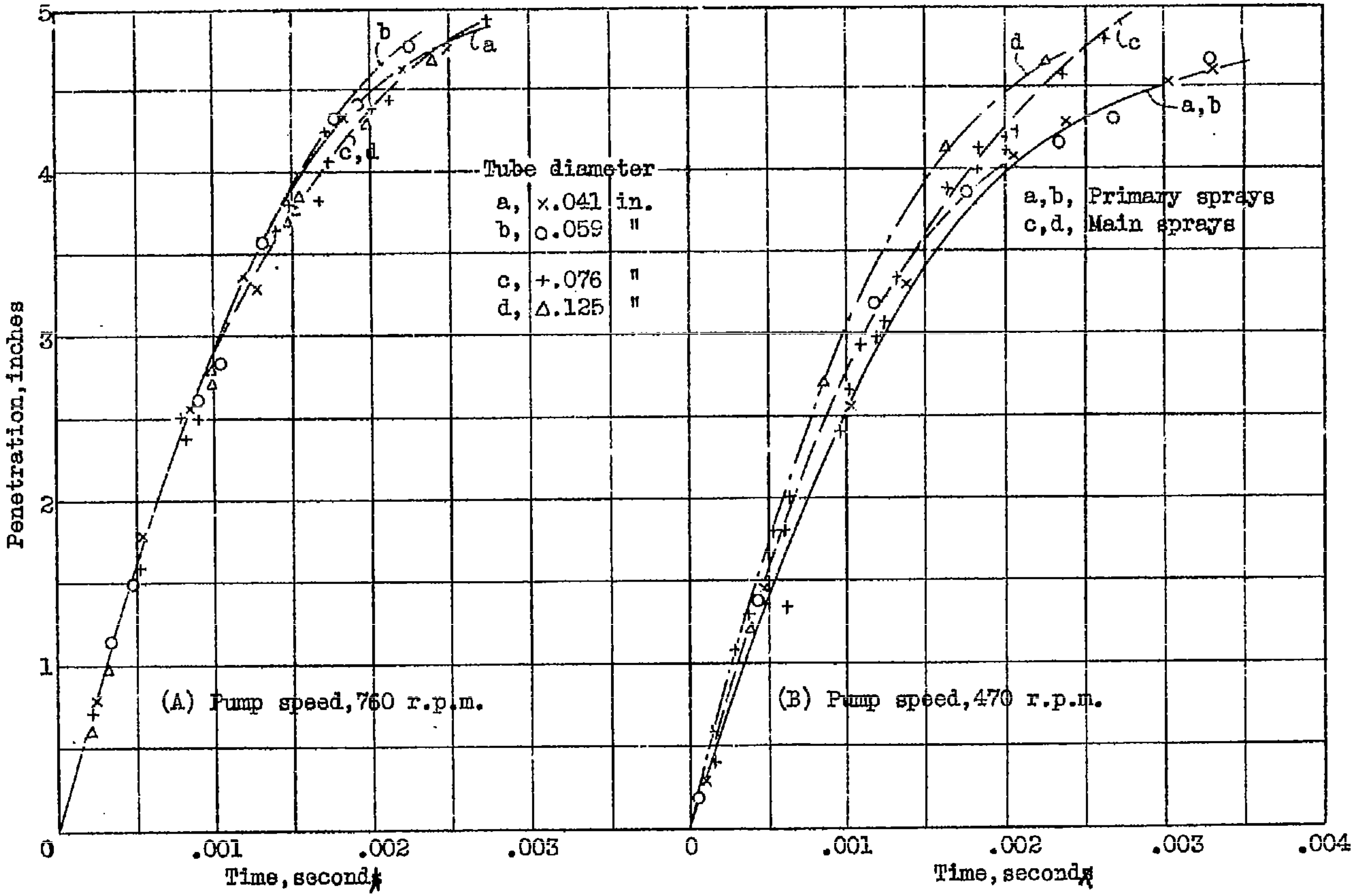

Fig.12 Effect of injection-tube inside diameter on spray-tip penetration. Injection-valve closing pressure, 2000 lb./sq. in. Tube length, 34 in. Orifice diameter, 0.020 in.

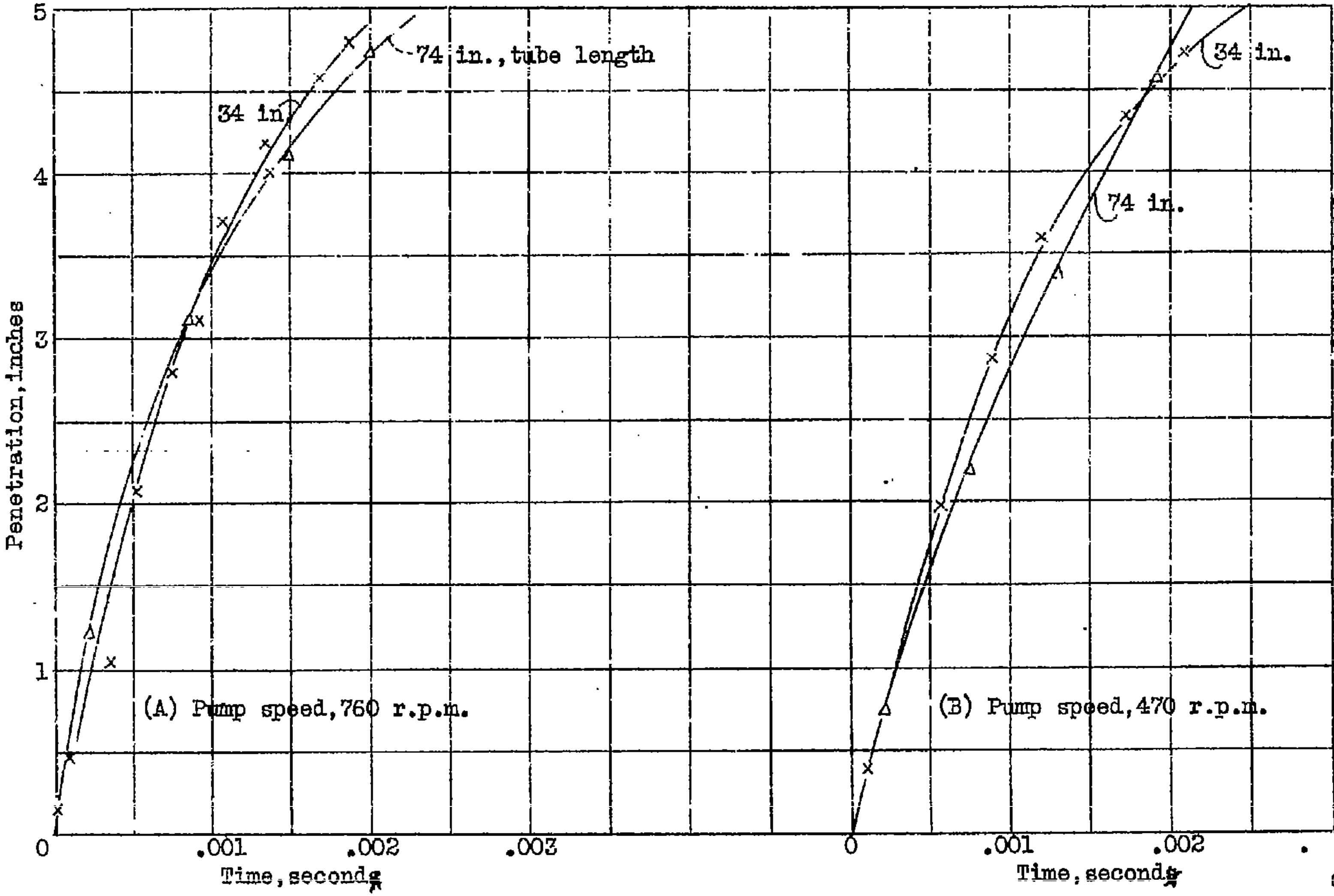

Fig.13 Effect of injection-tube length on spray-tip penetration. Injection-valve closing pressure, 2500 lb./sq. in. Injection-tube inside diameter, 0.125 in. Orifice diameter, 0.020 in.

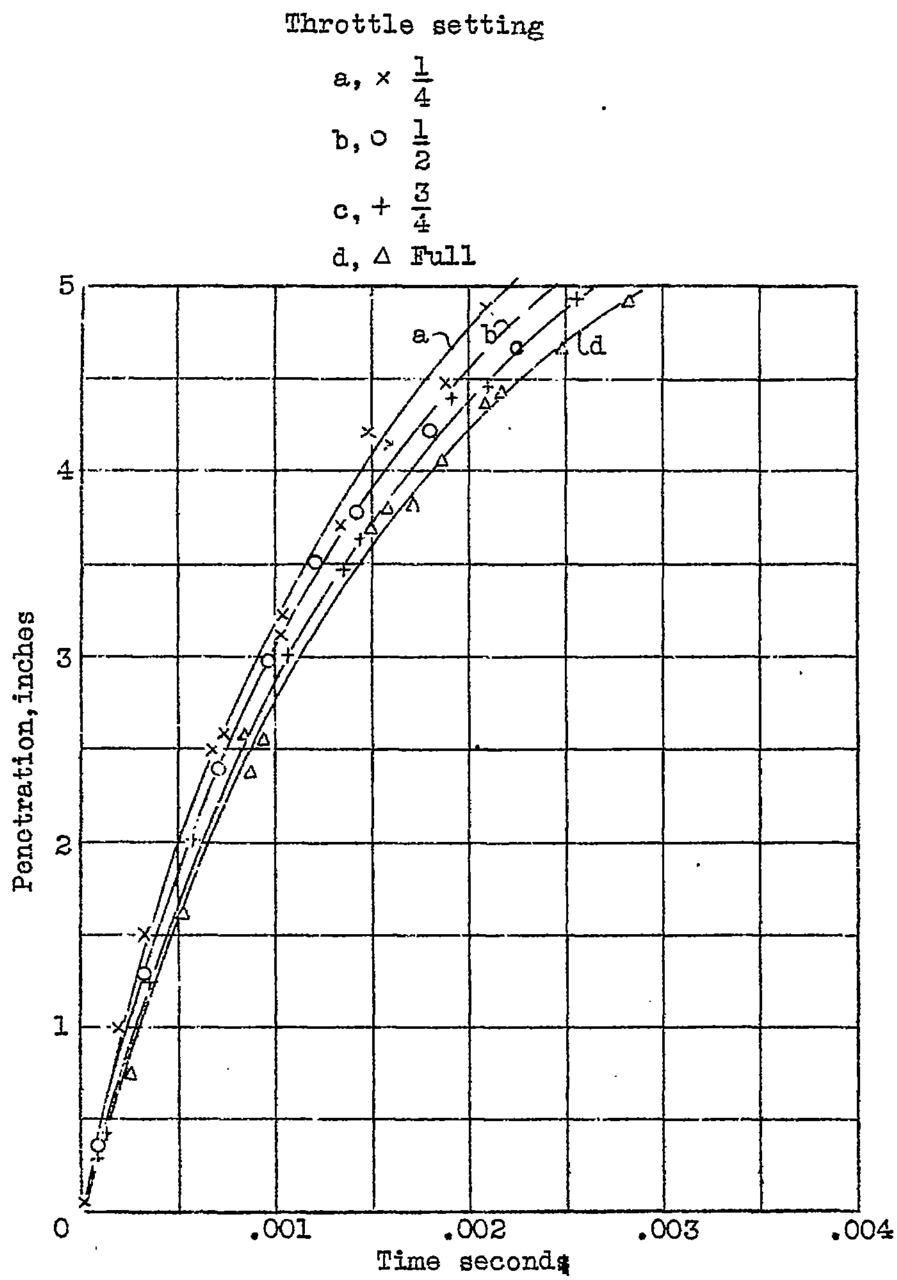

Fig.14 Effect of pump throttle setting on spray-tip penetration. Pump speed, 760 r.p.m. Injection-valve closing pressure, 2000 lb./sq. in. Injection-tube inside diameter, 0.076 in. Tube length, 34 in. Orifice diameter, 0.020 in.

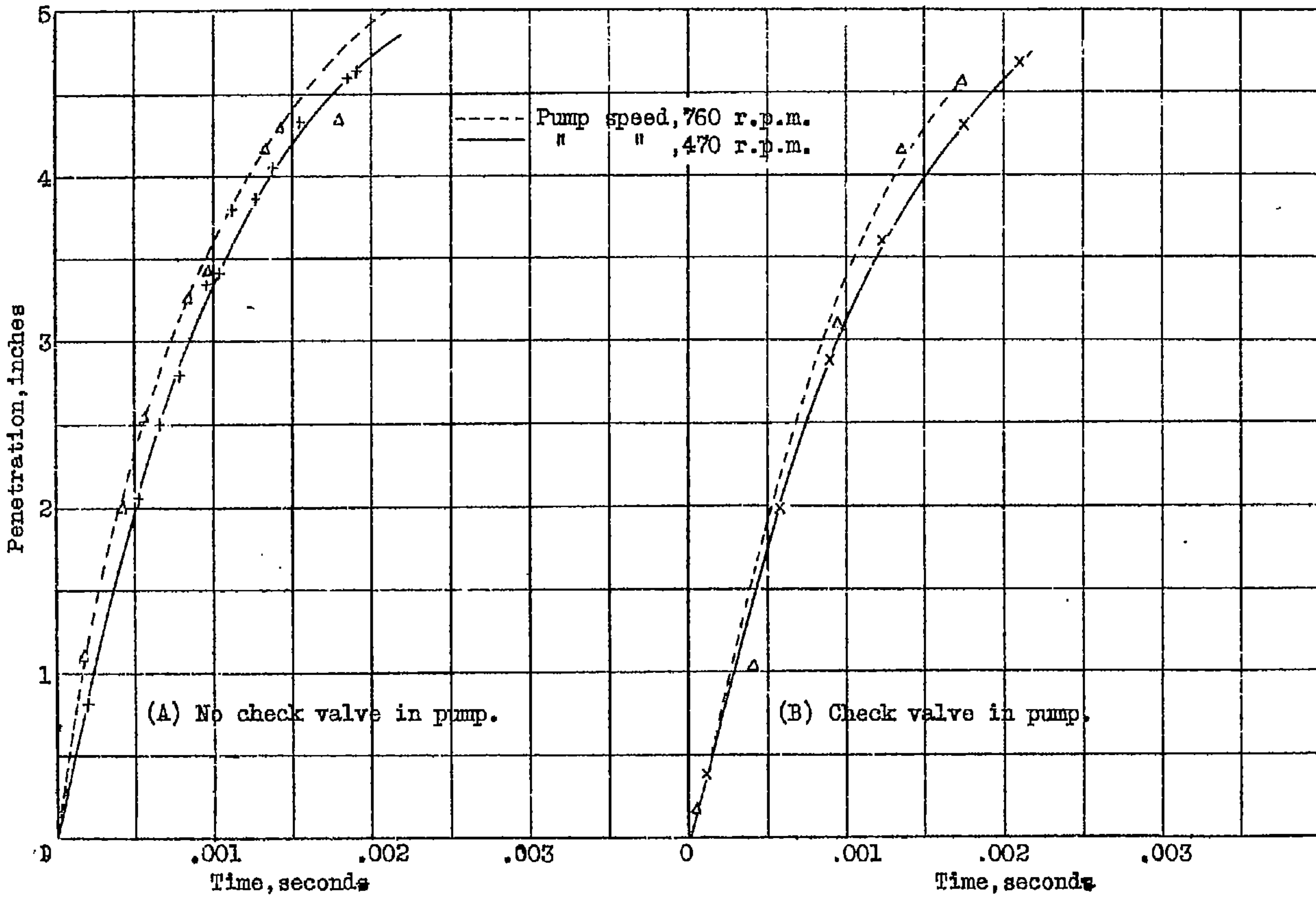

Fig.15 Effect of check valve on spray-tip penetration. Injection-valve closing pressure, 2500 lb./sq. in. Injection-tube inside diameter,0.125 in. Tube length,34 in. Orifice diameter,0.020 in.

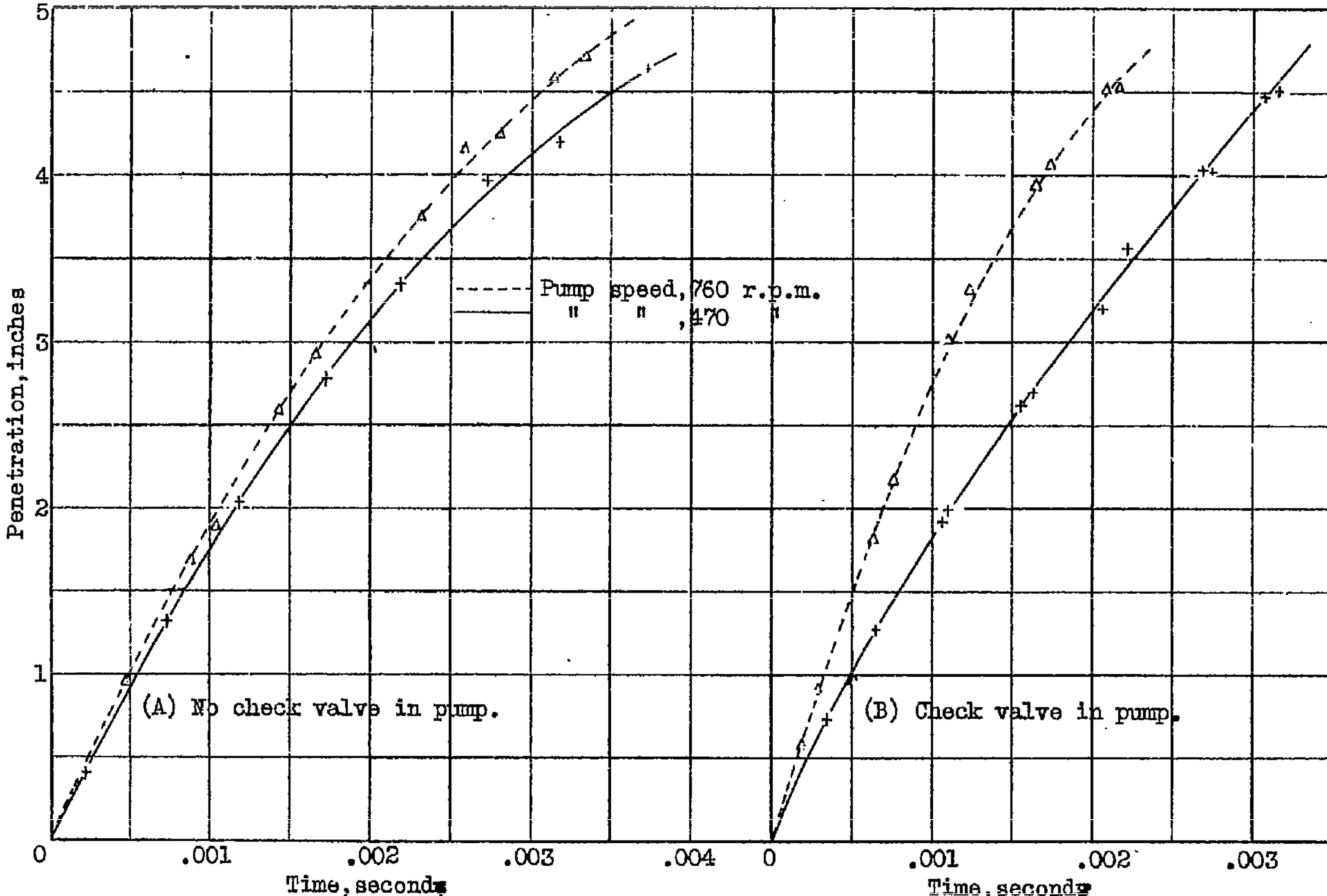

Fig.16 Effect of check valve and open nozzle on spray-tip penetration. Open nozzle. Injection-tube inside diameter, 0.125 in. Tube length, 34 in. Orifice diameter, 0.020 in.

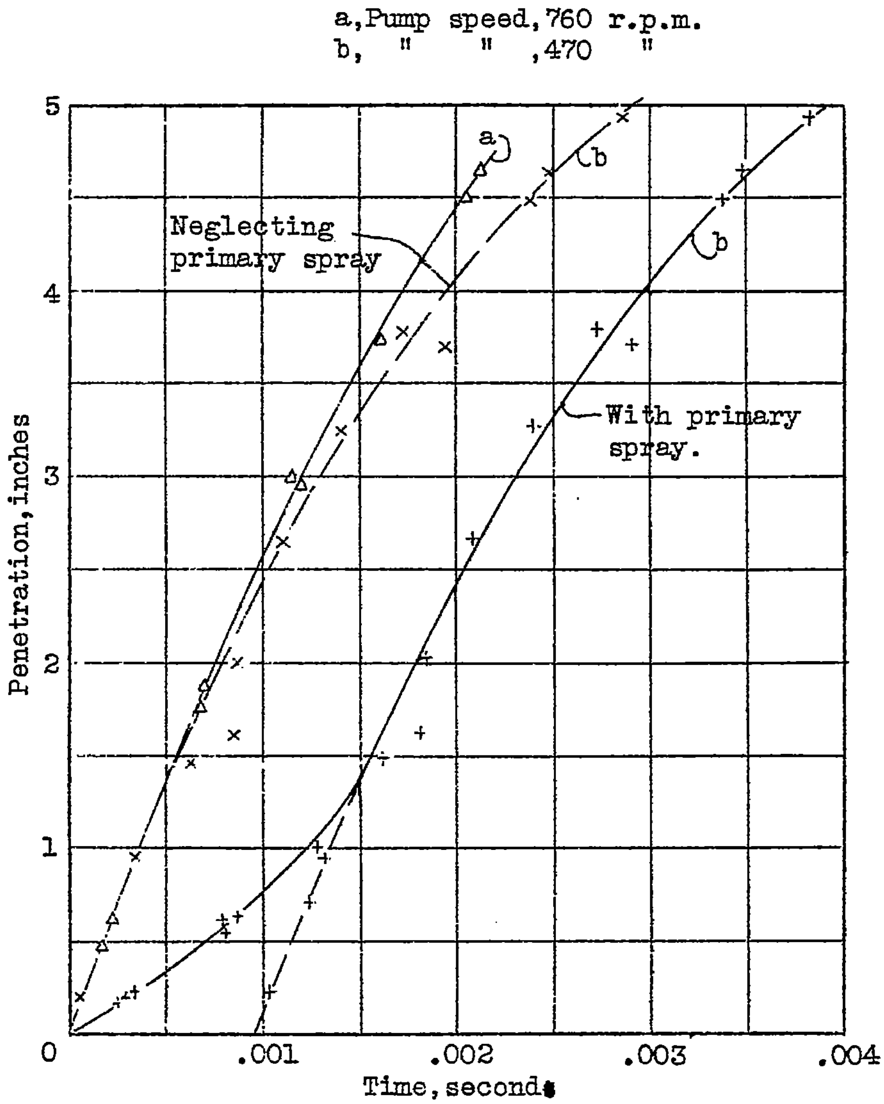

Fig.17 Spray-tip penetration with 0.030 in. orifice. Injection-valve closing pressure, 2500 lb./sq. in. Injection-tube inside diameter, 0.125 in. Tube length, 34 in. Orifice diameter, 0.030 in.

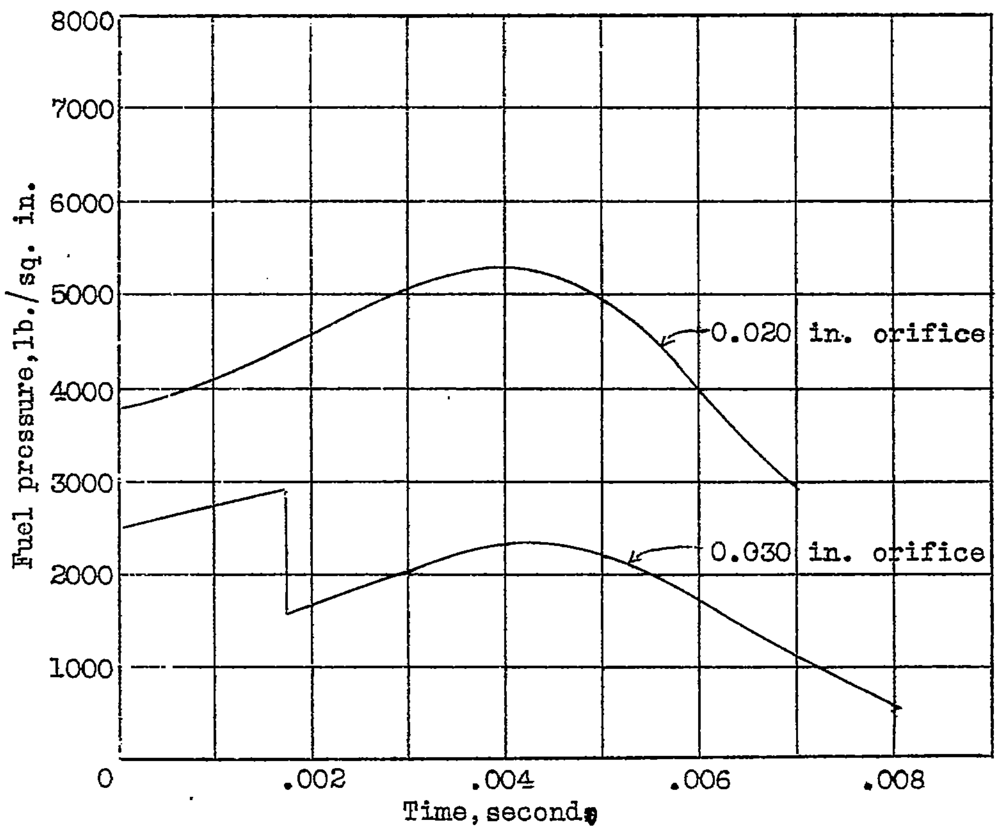

Fig.18 Instantaneous pressure at discharge orifice. Pump speed, 760 r.p.m. Injection-valve closing pressure, 2500 lb./sq. in. Injection-tube inside diameter, 0.125 in. Tube length, 34 in.

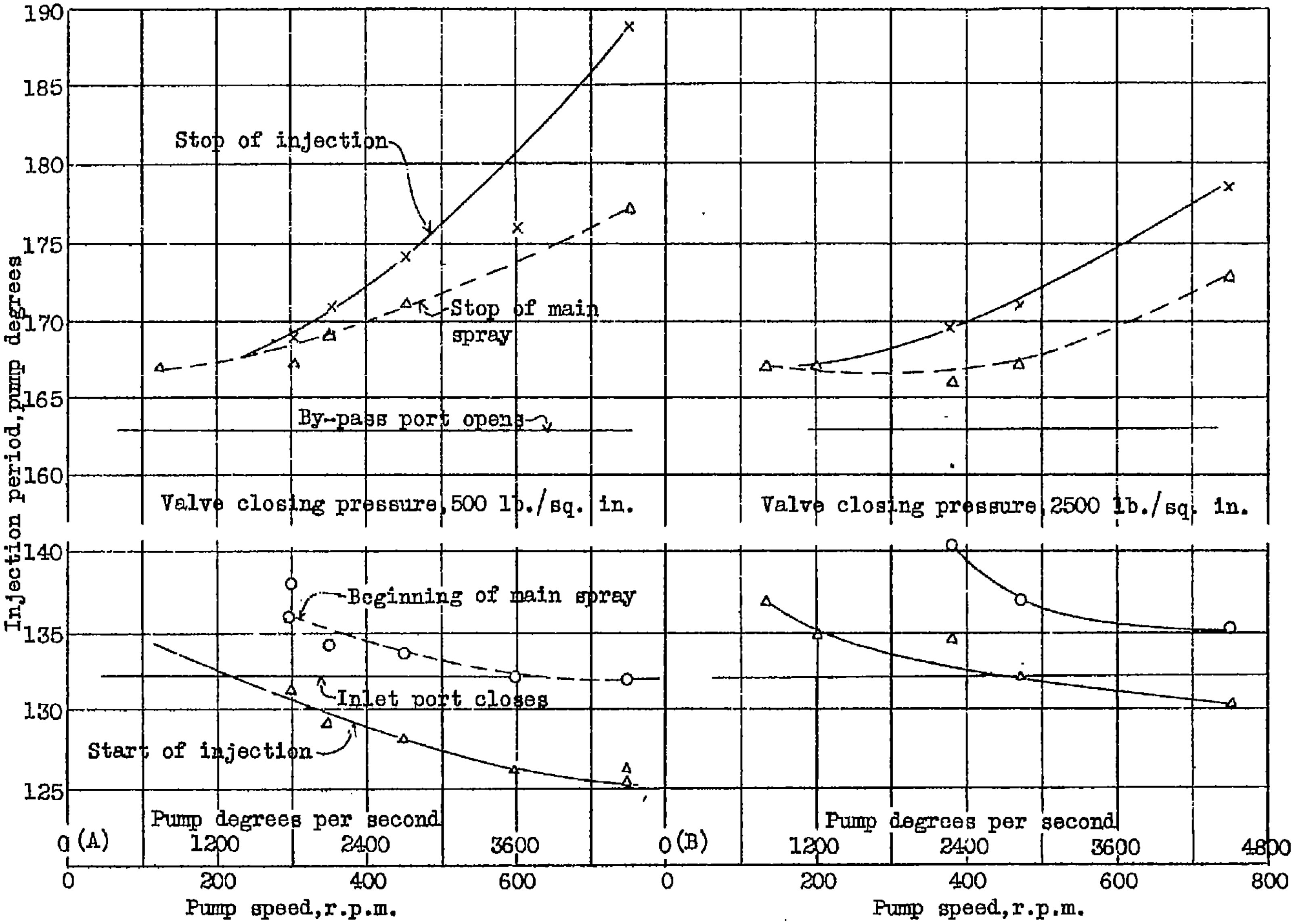

Fig.19 Effect of pump speed on injection lag and injection period. Injection-tube inside diameter, 0.125 in. Tube length, 34 in.

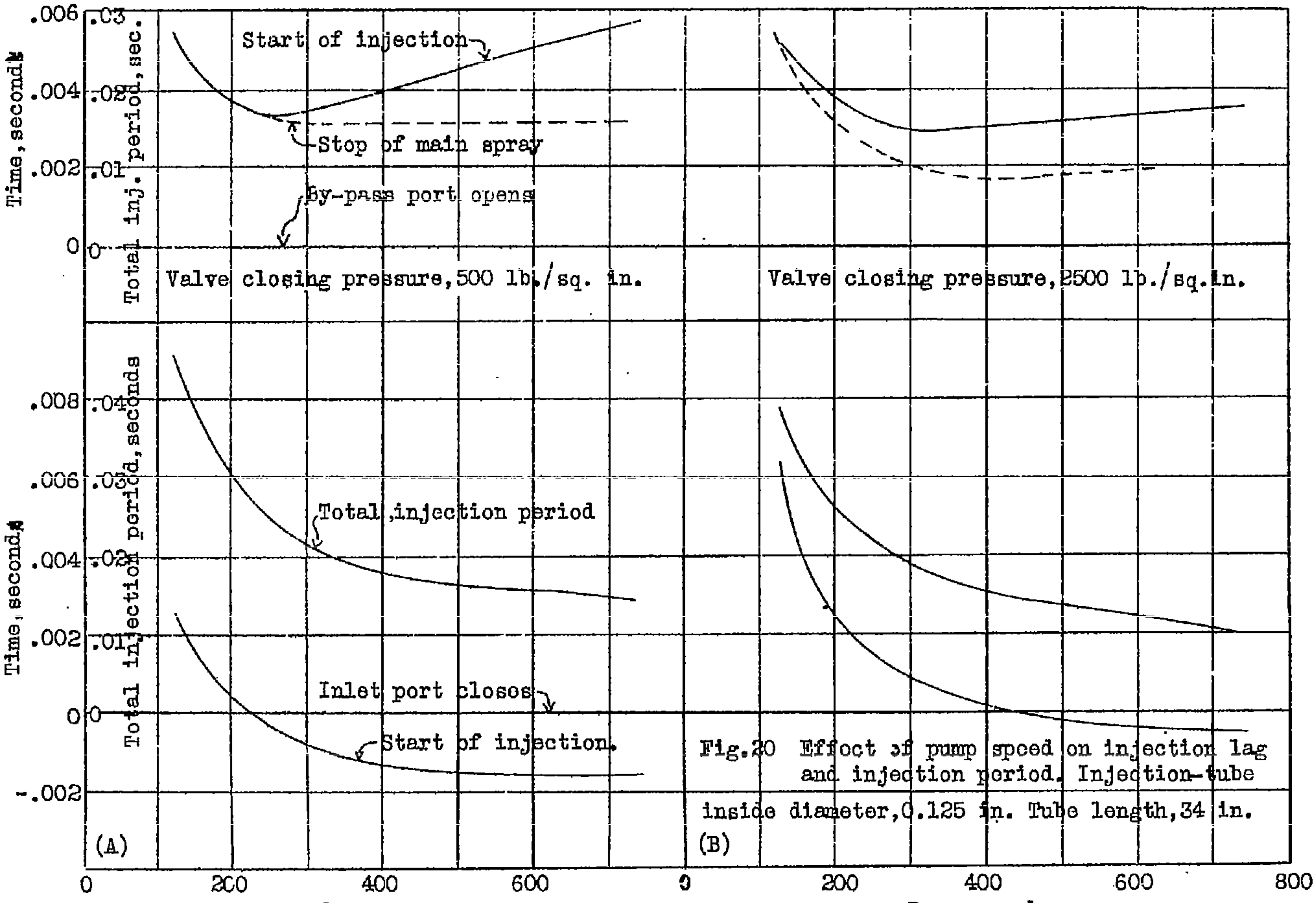

Fig.20 Effect of pump speed on injection lag and injection period. Injection-tube inside diameter, 0.125 in. Tube length, 34 in.

Fig.20

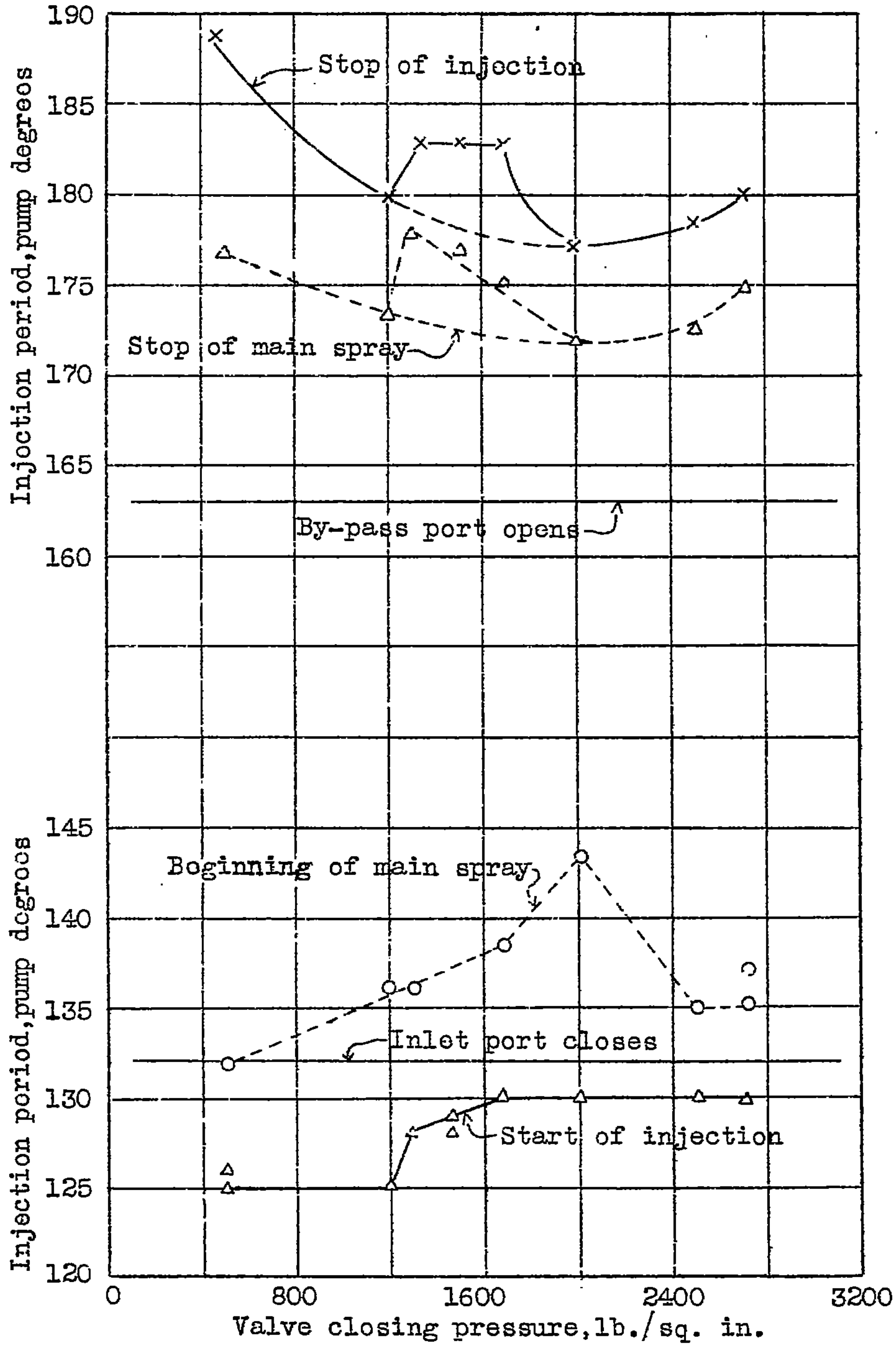

Fig.21 Effect of injection-valve closing pressure on injection-lag and injection period. Pump speed, 750 r.p.m. Injection-tube inside diameter, 0.125 in. Tube length, 34 in.

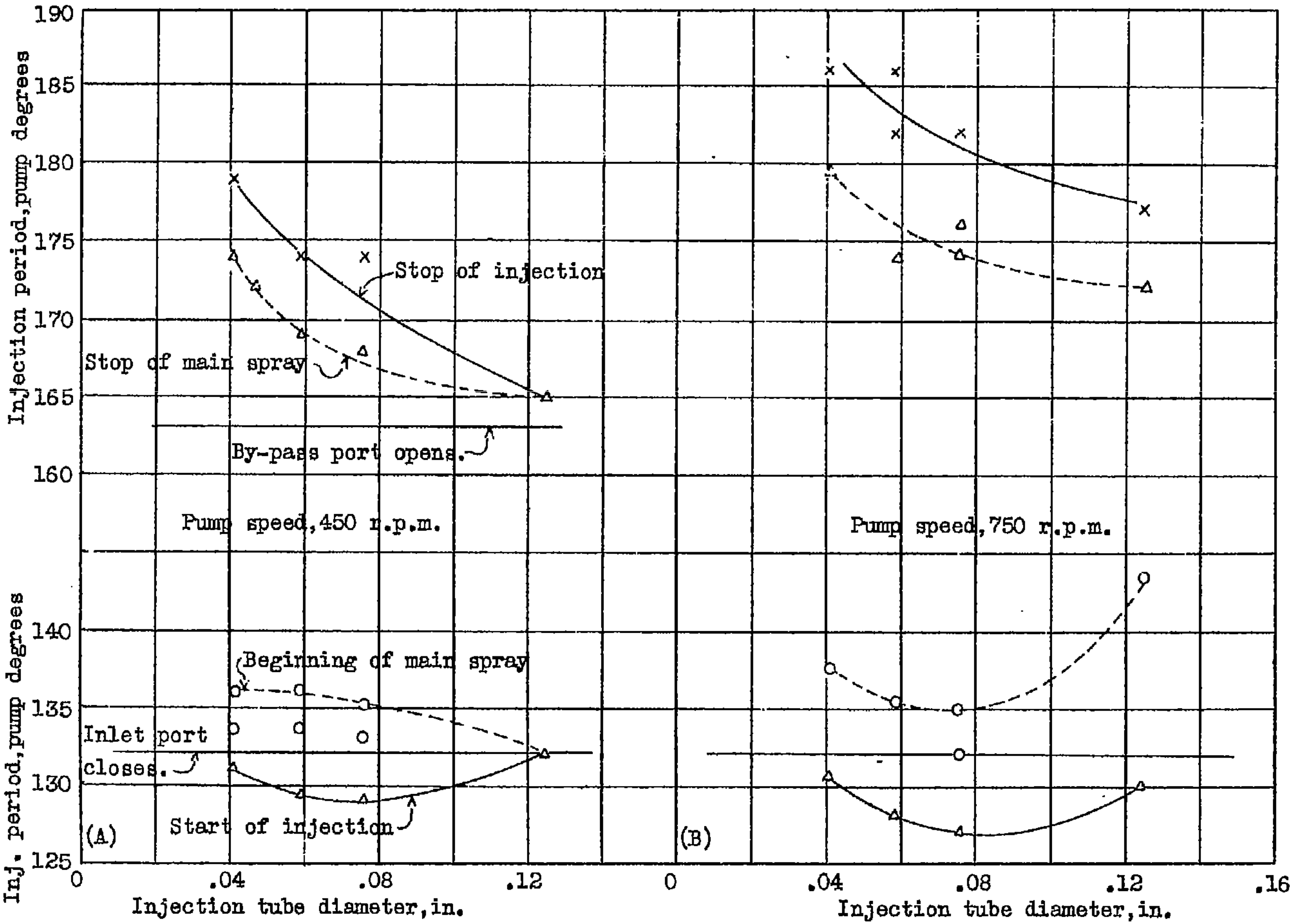

Fig.22 Effect of injection-tube inside diameter on injection lag and injection period. Injection-valve closing pressure,2000 lb./sq.in. Tube length,34 in.

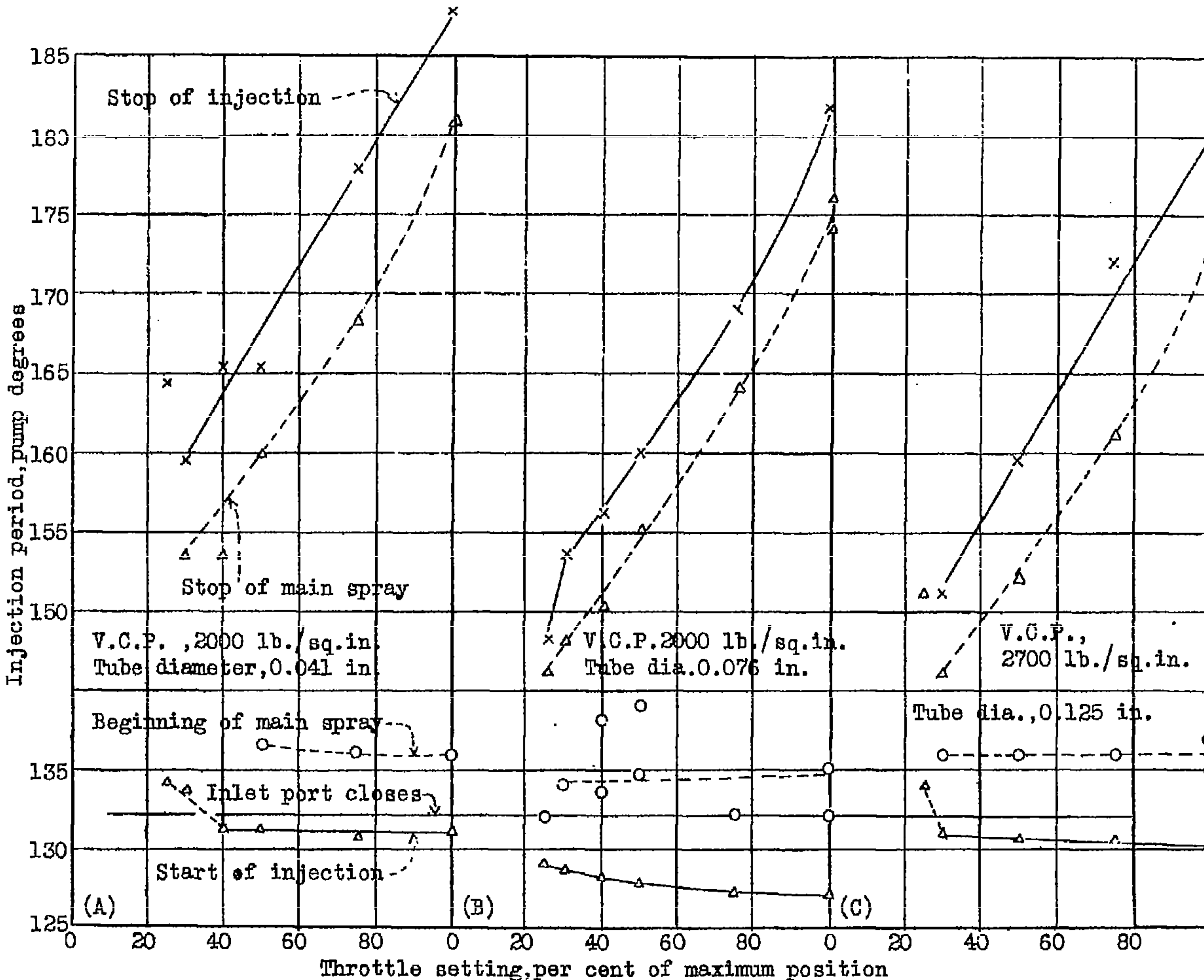

Fig.23 Effect of throttle setting and injection-tube inside diameter on injection lag and injection period. Pump speed,750 r.p.m. Tube length,34 in.